

# **Essential elements of the energy transition for freight movements: data mining, modelling tools and policy scenarios - with case study in New Zealand**

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*Ki ngā Tāngata o Aotearoa*

## Abstract

New Zealand's commitment towards the Kyoto Protocol and Paris Agreement requires a 70% reduction of current gross emissions by 2050. Oil's high energy return on investment, containerization, the expansion of the road network, and the deregulation of trucking have turned the freight sector heavily dependent on fossil fuel resources. This dependency represents a *wicked problem* whose solution requires a radical transformation of the system. This thesis is concerned with the development of a framework that channels the advantages of different modelling methodologies into delivering a future vision, a long term-strategic concept of a freight system that fully embraces feasible and systemic decarbonisation pathways.

The first part of the thesis presents a brief review on the historical evolution of the freight sector and provides current figures on both, energy and transportation sectors. Chapters 2 and 3 also explore state of the art energy and transport modelling methodologies, searching for limitations and advantages, which further lead into the conception of a new planning approach more aligned with the aim of the thesis. Chapter 4 covers the formulation of a framework for STRATegic COnccept DEsign of Freight Systems (STRATCODE). STRATCODE combines three components: freight distribution, network analysis and agent based Discrete Event Simulation (DES). The consideration of different components enhances the realization of different objectives, specifically addressing issues on data availability, absence of logistics features in transport modelling and long-term planning of freight infrastructure capacity.

The remaining chapters cover each of the components of STRATCODE in more detail and are also implemented using the North Island of New Zealand as a case of study. Chapter 5 describes the implementation of the freight distribution component. The key contribution of the distribution component was the identification of representative facility locations through the

exercise of web scrapping and sequential GIS processing tasks. Chapter 6 elaborates on the development of the optimization component, a GIS-based intermodal planning model. The contribution of the network planning approach relied on the architecture of the model's algorithm which enhanced multifold functionality, mainly allowing to deliver locations for intermodal terminals and to build a database with optimal shipping plans to be tested during simulation. Chapter 7 presented the last component, and agent-based discrete event simulation model. The simulation component was complementarily utilized to interrogate the capacity of the analytic solution delivered through the previous optimization component. The model was tested for different simulation experiments leading to the formulation of different concepts. An economic assessment was also carried out in order to identify the most cost-effective setup.

The results suggest that future investments should prioritize the development of intermodal hubs. These developments could lead to reductions in energy savings and GHG emissions of approximately 48% and 47%, respectively. The electrification of a congested railway segment can increase emissions reduction up to 54%, which is still far from the 70% needed. The difference against the national target could be further achieved at the expense of a significant reduction in transport activity related to non-essential commodities.



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I once heard a story about a little girl, who was able to solve complex logic games from a very young age, but was not given the credit she deserved, because the world around her was not able to assimilate the fundamental role of women in engineering and science. Fortunately, the little girl proved the world to be wrong and became a woman of science. I am referring to my supervisor, Professor Susan Krumdieck. My gratitude is to her, for inspiring new generations of men and women to bring innovation, dedication and commitment into shaping a brighter and prosperous future to our planet. Obviously, my gratitude goes to my co-supervisor, Professor Rua Murray. I would like to express my appreciation for his kindness, continuous support, encouragement and always constructive feedback.

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## List of Acronyms

ABM	Agent Based Modelling
ALICE	Alliance for Logistics Innovation through collaboration in Europe
ASC	Alternative Specific Constant
BAU	Business as Usual
BTMS	Bangladesh Transportation Modelling System
CGE	Computable General Equilibrium
CM	Consolidates Model
DES	Discrete Event Simulation
EOQ	Economic Order of Quantity
FIGS	Freight Information Gathering System
GDP	Gross Domestic Product
GHG	Greenhouse Gas
GIS	Geographic Information System
GUI	Graphic User Interface
ICT	Information and Communications Technology
IMF	International Monetary Fund
IO	Input-Output
InTIME	Interdisciplinary Transition Innovation, Engineering and ManagEment
IPCC	Intergovernmental Panel on Climate Change
IPFP	Iterative Proportional Fitting Procedure
ITS	Information Technology Solutions
LAMBIT	Location Analysis Model for Belgian intermodal Terminals

LCDB	Land Cover Database
LEAP	Long Range Energy Alternatives Planning
LINZ	Land Information New Zealand
LP	Linear Programming
LPC	Lyttelton Port Company
LQ	Location Quotients
LRIS	Land Resource Information Systems
LULUCF	Land Use Change and Forestry
MBIE	Ministry of Business, Innovation and Employment
MCDM	Multi Criteria Decision-Making
MCMND	Multi-commodity Multimodal Network Design
MNP	Multinomial Probit
MRIO	Multiregional Input Output
NCC	Network Communication Coordinator
NFDS	National Freight Demand Study
NZIFN	New Zealand Intermodal Freight Network
OD	Origin-Destination
OECD	Organisation for Economic Co-operation and Development
OLADE	Latin American Energy Organization
PI	Physical Internet
PKM	Passenger Kilometre
POA	Ports of Auckland
POT	Port of Tauranga
RUBMRIO	Random Utility Based Multiregional Input Output

SDSS	Spatial Decision Support System
SSTP	Shortest Spanning Tree Problem
STRATCODE	STRATegic COnccept DEsign of Freight Systems
SUPER	Unified System for Regional Electric Power Planning
SYMBIT	SYnchromodal Model for Belgian Inland Transport
SynchroMO	Synchromodal Modelling Operator
TAPAS	Transportation And Production Agent-based Simulator
TCC	Transport Chain Coordinator
TE	Transition Engineering
TEU	Twenty-Foot Equivalent Unit
TKM	Tonne Kilometre
TPES	Total Primary Energy Supply
VKT	Vehicle kilometres travelled

## **Chapter 1: Introduction**

The post-World War II era of cheap oil sustained the development of highways which virtually removed the barriers to geographic sprawl of residential, commercial, agricultural and industrial settlements. The preference for faster, cheaper and easier door-to-door deliveries allowed trucks to overtake the freight business

In 2017 the total energy consumption reached 9717.681 Mtoe (Million tons of oil equivalent), three time the demand of four decades ago, and the transportation sector was responsible for 27.89% of the total energy demand (International Energy Agency, 2017b). The outlook for the transport sector is critical since almost all means of transport are heavily dependent on fossil fuels like gasoline and diesel. For transportation, decoupling Gross Domestic Product (GDP) growth from Greenhouse Gas (GHG) emissions might be more challenging in contrast to other sectors like industry which already counts on feasible alternative technologies and cleaner fuels. In spite of the recent developments in energy efficient vehicles, GHG emissions from the transport sector were 7 Gt CO<sub>2</sub>eq in 2010 and they have been increasing at a faster rate than any other sector (Sims et al., 2014b). The strong reliance that transportation has on the oil market, poses a critical threat to future accessibility to essential activities and commodities, taking into account the finite nature of this non-renewable resource and its high price volatility. In response to this, a re-direction of investment would be essential. For instance, the European Union is aiming to make the freight transport system more environmentally-friendly, prioritizing upgrades on network and terminal infrastructure in order to absorb and cope the expected volume increase implied by a substantial modal shift to rail and waterborne transport (L. a. Tavasszy & J. van Meijeren, 2011). Although, advancement towards low carbon transportation systems will not only depend on major investments in infrastructure, but also rely on complementary measures within the supply chain involving changes in vehicle

technologies, substitution of energy carriers, relaxation of just-in-time deliveries and low carbon sourcing (L. a. Tavasszy & J. van Meijeren, 2011). Moreover, it is likely that the latter set of measures will require some level of government intervention.

This thesis acknowledges the environmental implications of an energy-intensive freight transportation system. Accordingly, it assesses carbon mitigation measures within the freight transport sector, particularly focusing on multimodal transportation and electrification pathways. More importantly, the thesis studies the limitations of conventional planning models and proposes a modelling toolbox that can aid the development of a transportation network concept that can potentially cope with future constraints on fossil fuel availability. This chapter delivers the motivation, problem statement and objectives of the research upon a broad literature review transportation system analysis and covers the role that promising modelling approaches can have as part of a robust framework.

## **1.1. Aspects of conventional energy and transportation modelling**

Work in this thesis is circumscribed within the area of transportation as an energy system. Often, the methods are focused on a specific perspective of the energy-transport nexus.

### **Energy Scenario Analysis**

In regards to energy planning, policy studies are based on aggregated statistics at the national or regional level and follow approaches that are similar to life cycle assessment and national accounting methodologies, so that emission intensities are aggregated into indicators that are later applied to the transport performance (tonne-kilometres or passenger kilometres) of every

transportation mode (Mattila & Antikainen, 2011). These models are often based on the assessment of energy scenarios and pathways that rely on forecasts of economic growth, anticipate changes in energy efficiency from the adoption and development of vehicle technology, and assume an energy mix that satisfies commitments to reduce emissions and energy demand (Emodi, Emodi, Murthy, & Emodi, 2017; Fan, Wang, Li, Yu, & Zhang, 2017; S. P. Krumdieck, 2017; Prasad & Raturi, 2018; Tsita & Pilavachi, 2017). Historically, long-range energy forecasts have failed to make accurate predictions as uncertainties resulting from concatenated assumptions on energy, environmental and socioeconomic developments and interactions are inherently difficult to account for (Smil, 2000).

### **Freight transport and trade**

On the other hand, the field of transportation system analysis has focused on the interactions between the socioeconomic and transportation systems within a region (Manheim, 1979). The required level of detail and modelling scope are strongly connected to the issues under investigation (Jong et al., 2016). Freight transport models have exploited the linkage between economic activity and commodity flow patterns to estimate transport demand and assess the impact of new transportation infrastructure (Bröcker & Korzhenevych, 2013; Kockelman, Jin, Zhao, & Ruiz-Juri, 2005). The modelling purpose has gravitated towards forecasting transport demand and predicting traffic. In many cases, statistical estimation is at the core of the methodology and often relies on vast commodity flow surveys (M. E. Ben-Akiva et al., 2016; Oka et al., 2019). Survey responses are mostly concerned with reliability, travel time, and cost attributes (Culotta, Fang, Habtemichael, & Pape, 2019; Rockpoint Corporate Finance Ltd, 2009; Shams, Jin, Fitzgerald, Asgari, & Hossan, 2017), and do not necessarily reflect the level of awareness or concern needed to effectively reduce energy use in transport and tackle ongoing global warming. Moreover, commodity flow surveys are costly, infrequent and need

to overcome confidentiality issues because firms are often reluctant to expose commercially sensitive information (M. E. Ben-Akiva et al., 2016; Lóránt Tavasszy & de Jong, 2014).

### **Aggregate Resolution**

In general, model inputs and outputs for both sides of the nexus are generally aggregated or expressed in macro terms. There is a high level of complexity in integrating spatial variables into a reference energy system and also in describing the origin/destination characteristics of mobility and logistics (Gerboni, Grosso, Carpignano, & Dalla Chiara, 2017). On the other hand, it is also complex to assess energy use given different technologies, modes of transportation and uncertain utilization factors. The limitations on the aforementioned modeling methods denote missing interconnections between them and suggest the need for the development of more integrated operational tools that are capable to determine freight transport demand and enhance the identification of systemic carbon-reducing policies at each level of a territorial scale (Gerboni et al., 2017; Grenzback et al., 2013; Sims et al., 2014b; Lorant Tavasszy & de Jong, 2013).

### **Logistics**

In state-of-the-art freight models, data is aggregated over several geographical zones and possesses an interregional resolution (de Grange, Fernandez, & de Cea, 2010). It does not account for inventory and transport logistics services (Lorant Tavasszy & de Jong, 2013), which are essential features of freight transport. Aggregate data often fails to describe the structure of underlying logistics operations, as the pattern of shipments within a freight system is lost and replaced by patterns that respond differently to changes in transportation attributes (Friedrich, Tavasszy, & Davydenko, 2014). Moreover, the aggregated nature does not



contribute in capturing the heterogeneity of actors involved in the transport market (V. Reis, 2014). Bridging the gap between micro and macro distribution structures is a relatively new area of freight transport modelling research. Recent freight models are evolving from the classic four-stage framework and embracing transport and inventory logistics (Moshe Ben-Akiva & de Jong, 2013; Combes, 2014; Jong et al., 2016). The adoption of logistics enables a more complex decision-making process involving choices on product location and planning, sourcing, shipping, warehousing and transport management (L. A. Tavasszy, Ruijgrok, & Davydenko, 2012). Logistics features are at the core of freight transportation, and simulation is gaining acceptance due to its capability to incorporate the heterogeneity of actors, commodities and processes associated to freight supply chains (Baindur & Viegas, 2011; Holmgren, Davidsson, Persson, & Ramstedt, 2012; Liedtke, 2009). Recent approaches embrace structural components from multi-agent supply chain dynamic models (Swaminathan, Smith, & Sadeh, 1998) and can also enable decision makers to assess the performance and capacity of freight systems, identify bottlenecks and weigh the impact of different interventions on transport technology and infrastructure.

## **1.2. Need for an integrated and long-term vision of the transportation system**

The re-organization required to transition from growth in energy and material consumption to a regenerative economy will pose many challenges for countries. In the case of freight transportation, supply chains have become dependent on resource-intensive truck transport, globalized market access and just-in-time procurement. There is a need to devise integrated models for analysis and planning of freight transportation systems so that, in the future, models can overcome environmental constraints and potential limitations on the use of energy resources. These issues have been endorsed in a report from the Intergovernmental Panel on

Climate Change (IPCC) which points out that that contemporary models lack the ability to interpret the impact of behavioral and infrastructural changes (Sims et al., 2014). Models based on travel surveys are relevant for short and mid-term decision making but may not be practical for long-term planning because current choices do not prioritize energy consumption attributes. Instead, a more adequate pathway is required to build and manage the “best” operation plans to achieve desired levels of cost versus quality of service versus environmental and societal impacts, and to evaluate strategies and policies (Teodor Gabriel Crainic, Perboli, & Rosano, 2018). In the context of freight transportation strategic planning, the field of multimodal network analysis offers a variety of modelling approaches that can adopt carbon reducing strategies as modelling constraints. Previous examples have adopted GIS-based intermodal optimization tools to assess the impact that hypothetical trade-offs (time vs. energy use) can have over intermodal network configurations (Asuncion, Rendall, Murray, & Krumdieck, 2012; Caris, Macharis, & Janssens, 2012; Winebrake, Corbett, Hawker, & Korfmacher, 2008). Intermodal transportation planning has been gaining attractiveness as a research area that can offer planners the opportunity to design and promote efficient freight transportation with good mobility and reliability (Macharis & Pekin, 2009; SteadieSeifi, Dellaert, Nuijten, Van Woensel, & Raoufi, 2014). The integration of Geographic Information Systems (GIS) is relatively new, and it has improved model functionality, usability, and enhanced a clearer visualization of impacts (J. Winebrake et al., 2008).

Transition Engineering (TE) is an emerging field that aims to identify viable economic and technical changes that will enhance existing systems by maintaining their essential services while eliminating their dependency on fossil fuels. TE is based on a strategic framework: the interdisciplinary transition innovation, engineering and management (InTIME) approach. The InTIME approach is used to identify and implement “down-shift projects” that can transform

an activity system to much lower energy, mineral and natural resource (S. P. Krumdieck, 2017). It entails seven steps that build knowledge and understanding of an activity system from different perspectives.

New methods developed with this concept are intended to aid policy makers and planners in identifying choices involving changes in land use, options for infrastructure and technology investment and incentives to efficiently reduce vulnerability and risk, increase adaptive capacity and build resilience (S. Krumdieck, 2011). Most of the TE-related breakthrough modelling approaches within the transport field are based on the assumption that infrastructure, activities and travel behavior will change in order to cope with fuel shortages. Changes involve mode shifting, destination shifting, efficiency improvement, and trip elimination. Energy shortage risks can be quantified, assessed and considered as part of urban and transportation planning decisions and travel demand patterns and changes are subject to availability of energy (Dantas, Page, & Krumdieck, 2007). The generation of a path-breaking concept is a core step of InTIME. Work in this thesis acknowledges the need for a long-term concept that departs from past trends of resource intensity and considers the potential of multimodal transportation planning and discrete event simulation in delivering feasible engineered alternatives to guarantee long-term functioning of the freight supply chain. Moreover, the combination of optimization and simulation-based methodologies offer promising advantages, specifically the needed ability to connect the multiplicity of analytical perspectives on the critical shaping factors and opportunities for accelerating change (Turnheim et al., 2015). New ways are needed to assess sustainability transitions pathways, delineate a vision and a way forward.

### **1.3. Objectives of the thesis**

The primary research question is: *how to build a decarbonized freight system?* This thesis takes an engineering perspective, focusing on what infrastructure can be built, and what systems are needed to support the freight task and shift from energy-intensive road transportation. The specific work in this thesis develops a modelling framework for the strategic planning of national freight systems and demonstrates how to identify cost-effective low carbon transition pathways. The study has four different significant components:

- Reviewing the evolution of the freight sector at a global and local scale.
- Studying the limitations of conventional modelling approaches.
- Developing an integrated framework that could assist the construction of a long-term concept for the freight transportation system.
- Implementing an integrated framework using New Zealand as a case of study to deliver a portfolio of cost-effective interventions on freight infrastructure.

### **1.4. Scope**

The thesis uses New Zealand as a case of study. Relevant figures on New Zealand's past and present energy and transport sectors are presented in order to highlight current and past unsustainability trends in the freight transport sector. The literature review covers modelling methodologies from both, the energy and transport planning perspectives, looking to find strengths and weaknesses in the state-of-the-art. The literature review also addresses future directions of research in order to cope with the need to embrace environmental and logistics considerations in long-term freight system planning. State-of-the-art energy planning and

freight transport models are implemented to corroborate modelling advantages and limitations cited in the literature. Upon research and experimentation with conventional modelling approaches a new methodological framework is put forward consolidating different components that address issues on data availability, long-term strategic planning, absence of logistics elements and identification of strategic carbon-reducing pathways for the freight sector. The proposed framework is tested for the New Zealand context and a portfolio of interventions on infrastructure is proposed.

## **1.5. Chapter Overview**

**Chapter 2** presents an overall literature review from the energy planning and the transportation analysis perspectives. The chapter also describes modelling limitations that prelude an overview of the direction where freight transportation planning is heading, covering definitions and studies on multimodal network planning, cooperative schemes, adoption of logistics features through simulation and integral approaches that combine optimization with simulation.

**Chapter 3** presents an overview of the history of freight transport in New Zealand and provides facts and figures relevant to the sector. The chapter also provides insights of the evolution of the sector on a broader scale, highlighting the events and technological changes that drove the sector into an unsustainable path.

**Chapter 4** presents an energy and environmental planning model used to map the energy sector in New Zealand and provide a perspective of different scenarios associated to changes in activity, modal share and technological interventions on the transport sector.

**Chapter 5** presents the methods and results associated to the development of a Random Utility Based Multiregional Input Output Model. The model is used to implement a sensitivity analysis of freight origin and mode choice in response to changes in fuel prices. Findings from this chapter allow to corroborate modelling limitations exposed in the scientific literature and also expose issues that may have been previously overlooked.

**Chapter 6** introduces the main contribution of this thesis: a framework for STRATegic COnccept DEsign of Freight Systems (STRATCODE). STRATCODE integrates different components in order to tackle some of the issues covered in the literature review and also encountered upon experimentation with the state-of-the-art. The chapter describes the purpose of each component, data inputs and outputs, and the relevant connections and interactions.

**Chapter 7** describes the structure of the first component, a freight distribution model that encompasses iterative proportional fitting, the calibration of spatial interaction models and linear optimization. The methods are implemented to deliver disaggregated facility to facility matrices for different sectors and commodities. The component also allows to mitigate data availability issues.

**Chapter 8** presents the implementation of a Geographic Information System (GIS) based multimodal network analysis. The main outcome of the assessment is a geographic database containing information on commodity traffic and energy use for every link in the network under different cost considerations. Moreover, the model delivers the location of intermodal terminals and shipping plans under different optimization criteria. The component presented in this chapter is at the core of STRATCODE and its architecture gives room to connect the perspectives of strategic and operational planning layers.

**Chapter 9** presents the development of a GIS-based discrete event simulation model. Trucks, trains, terminals, and resources (i.e. cranes, forklifts) are modeled as agents that interact with each other in response to daily shipping plans queried from a database. The model adds a logistic component to complement transport modelling methodologies addressed in previous chapters and identifies cost-effective interventions on transport infrastructure.

**Chapter 10** presents the overall conclusions of the study and discusses possible opportunities for future work.

## **1.6. Summary**

This chapter presented the motivation for this research and an introduction to the models developed, validated, and executed within this thesis. Overall, freight transport's dependability on fossil fuel poses a significant risk to the economy, and there is an urgent need to plan for a resilient system capable of delivering essential services at the minimum energy cost. The availability of disaggregated freight data is crucial for the development of holistic approaches that consider the heterogeneity of agents and commodities, and the logistic operations and resources involved. Certainly, the freight system is highly complex, and there is a need to frame the assessment upon a long-term vision that prioritizes the optimal use of energy resources. Transition Engineering is a methodology that embraces this constraint as a forward operating environment which leads to a path break concept of the future. This thesis proposes a combined optimization/simulation approach to understand the limitations given by the current state of the freight network. Moreover, it embodies principles of TE to deliver a vision: a future concept of an intermodal system aligned with New Zealand's long-term commitments towards climate change mitigation.

## **Chapter 2: Literature Review**

The topic of this thesis is circumscribed within the area of transportation as an energy system. Accordingly, this chapter presents a literature review from both, the energy planning and the transportation analysis perspectives. The interaction between transport and energy systems has been studied through the implementation of energy and environmental planning models, and the chapter starts by providing some examples and applications cited in the literature. The review on energy planning is especially concerned on the utilization of the Long Range Energy Alternatives Planning (LEAP) Software, as it was used throughout the thesis as an emissions calculator model. Later, the focus is shifted towards the transportation analysis side, specifically within the context of freight transport, where input output analysis has been at the core of freight transport demand models. The chapter also presents a review on distribution structures that are applicable for freight transportation, with special emphasis on gravity-based formulations. The remaining sections present an overview of the direction where freight transportation planning is heading, including a review on multimodal network planning, cooperative schemes, adoption of logistics features through simulation and integral approaches that combine optimization with simulation within a strategic planning environment. The chapter allows to delineate limitations of conventional modelling approaches, which are further examined in Chapters 4 and 5.

### **2.1. Energy and Environmental Planning models with a transportation component**

Energy-environmental planning models are based on scenario analysis that project energy consumption and GHG emissions upon projections of socio economic indicators and elasticity functions. Common scenarios are based on long-term energy consumption with considerations



for environmental aspects, technology substitution, energy carriers' substitution, energy efficiency programs and implementation of Renewable Energy projects. Models that have a strong transportation component also emphasize on the forecast of Vehicle Population, Traffic Volume and Vehicle Kilometers travelled (VKT) per capita (Sadri, Ardehali, & Amirnekooei, 2014). Both energy and emissions from transportation are often calculated through a decomposition methodology that can also be embraced to understand the impacts that policy tools may have over the distinct factors that are contemplated within the analytical framework. The main factors that are considered in this analysis, also called ASIF, are taken to be Activity (ton-km), model Structure (share of activity for each mode), energy Intensity (energy used per unit of activity for each mode) and the Fuel to Carbon ratio (carbon released per unit of energy burned (Fulton, Cazzola, & Cuenot, 2009). The framework is defined through the following mathematical expression (3-1):

$$G = \sum_{modes} \sum_{fuels} A_{mf} S_{mf} I_{mf} F_{mf} \quad (3-1)$$

Schipper, Scholl, & Price (1997) originally formulated and applied the ASIF methodology in order to analyse trends in freight activity and energy use in 10 industrialised countries. Their analysis showed that freight activity increased roughly at the rate of GDP for the period that was studied (1973-1992) (Schipper, Scholl, & Price, 1997). Nowadays, the methodology has been widely accepted as an analytical tool for energy policy analysis. The Mobility Model (MoMo) used by the International Energy Agency (IEA) is a technical-economic spreadsheet and simulation model that allows users to define scenarios with different types of vehicles, fuels, efficiency levels and travel levels. Another common bottom-up method for the estimation of energy in road transportation focuses on the Vehicle Kilometres Travelled (VKT) rather than on transport activity. He et al. (2005) adopted this approach to estimate oil consumption and CO<sub>2</sub> emissions from China's road transport sector between 1997 and 2002. The vehicle

population and share of vehicle type were obtained from several sources including the National Statistical and Automotive Industry yearbooks. VKT was derived from freight and passenger traffic volumes, volume, share and average load capacity. Fuel economy was derived from the labelled fuel economy (measured under optimal speed) and an adjustment factor that represents features such as vehicle age, driving habits, fuel quality, amongst others (He et al., 2005).

### ***2.1.1. National Energy Systems Planning***

On the energy side, there are several software tools that have embraced the bottom-up approach mentioned in the previous section. The Unified System for Regional Electric Power Planning (SUPER) is a modeling tool developed by the Latin American Energy Organization (OLADE). SUPER can model mid to long term expansion of power and transmission capacity of an interconnected system; it also optimizes cost and minimizes energy risk (Latin American Energy Organization, 2018). EnergyPLAN is a model developed and maintained by the Sustainable Energy Planning Research Group at Aalborg University. EnergyPLAN simulates the operation of national energy systems (EnergyPlan, 2018). The LEAP System is a scenario based modelling software developed and maintained by the Stockholm Environment Institute; it can provide useful insights from the analysis of energy consumption, production and resource extraction processes within an economy. Fan et al. (2017) used LEAP in a Beijing case study and estimated energy demand and GHG emissions for different energy-conservation scenarios including an increase in the service volume of public transport, the replacement of traditional motor vehicles by alternative technologies and fuels, and the development of transport sharing schemes. Tsita and Pilavachi (2017) also used LEAP to assess different pathways towards decarbonizing the Greek road transport. Their scenarios were mainly focused on an increased use of electro-mobility and biofuels within the Light Duty Vehicle fleet (Tsita & Pilavachi,

2017). Prasad and Raturi (2018) also carried out a scenario-based analysis with LEAP, including changes in fuel and vehicle technologies, and considering a modal shift to non-motorized modes and the promotion of eco-driving in freight transportation. Other studies, model scenarios as integral plans, ranging from moderate to aggressive national strategies, and account for parallel interventions on different branches of the energy system, including the transport sector. For instance, the scenarios formulated by Emodi et al. (2017) consider the Nigerian's National Energy Master Plan that accounts for the concurrent expansion of electricity capacity, improvement of energy transmission systems, technological changes in residential lighting and diversification of fuel use in the transport sector. Nieves, Aristizábal, Dynner, Báez, and Ospina (2019) evaluates Colombia's energy system and formulates two future scenarios, differentiated by trends in economic growth, technological changes and substitution of petroleum based fuels. In regards to the road transport branch, their study explores the impact of an increase in participation of motorcycles and electric vehicles (Nieves et al., 2019).

### ***2.1.2. Freight Transportation System Analysis***

Much of the research efforts have been put onto passenger transportation and the main reason for this is that the mechanisms underlying freight transportation demand are considerably more complex than those for passenger demand. To a certain extent both fields, passenger and transportation, share the same foundations. However, commodities in freight transport are immensely heterogeneous and its movement involves more actors than the movement of passengers.

Historically, the field of transportation system analysis has derived transport activity upon the interactions between the socioeconomic and geographic features within a region. The theory has been based on the idea that flows or volumes moving through the system are subject to changes in the transportation system, like the introduction of a new highway port or railway, so that the level of service follows these transportation options. Shifts in demand can either be induced by exogenous factors such as population growth or by the transportation service level itself. For instance, in the context of passenger transportation, the expansion of suburban residential areas may accompany the development of a new highway. Changes or transport options have been incorporated into the models as decision variables. The core of the analysis has relied on the prediction of flow patterns, that is, anticipating the impacts associated with service and demand functions that are defined through decision variables (Manheim, 1979).

The traditional approach to deal with transportation systems is the four step aggregate demand model (Ortúzar S & Willumsen, 2011). Sophisticated freight demand models incorporate macroeconomic analysis into the traditional methodology, that is, origin destination freight flow matrices are derived through mathematical formulations that define patterns of economic exchanges between regions and economic sectors. State of the art models within this category include Multiregional Input Output (MRIO) and Computable General Equilibrium (CGE) Models.

A new generation of MRIO models incorporate functional forms from random utility theory, allowing trade flows to respond to changes in transportation costs. Kockelman et al. (2005) describe the calibration and application of a Random Utility Based MRIO model for Texas which use variable trade coefficients. The model was applied to study the effects of export demand changes on industry distributions and on regional trade flows. The variable trade

coefficients account for the impact of transportation costs, but MRIO models still lack the capacity to respond to changes in prices and are purely driven by predetermined final demands.

CGE models stand as an alternative for Input-Output (IO) models since they preserve the straight-forward modelling capacities while compensating for limitations. The structure of CGE model is based on a set of equations that represent the behaviour of the agents involved (households, government, and businesses) and a set of technological and institutional constraints (Ivanova, 2014). In a CGE model, technical coefficients and final demand vectors are endogenously determined through the specification of trade functions with constant elasticities of substitution, overcoming the fixed technical coefficients assumption from MRIO models (Brocker, 1998). Bröcker, Korzhenevych, and Schürmann (2010) applied a Spatial CGE to evaluate development of trans-European networks for the reinforcement of economic and social cohesion in the region. The model is based on a household and a production sector with two industries and trade costs dependent on the state of the infrastructure. Upgraded links represent lower trade costs and consequently, higher welfare of households in the region (Bröcker et al., 2010). Data availability can still represent a major drawback depending on the method used to construct the model, as its quality is to some extent dependent on the quality of the data (McKittrick, 1998).

The linkage between economic activity and commodity flow patterns is a feature that has been conveniently exploited to forecast freight activity under distinct socioeconomic scenarios. Freight activity can be further analyzed and processed in order to estimate the energy (fuel) that is needed to run the system. Traditional approaches have focused on the characterization of flows and corresponding use of resources, but still lack the ability to consider the effects of fuel prices and modal shifts (Grenzback et al., 2013).

On the other hand transport emission and energy consumption models follow approaches that are similar to life cycle assessment and national accounting methodologies. The model presented in the Chapter 4 is a clear example of this technique, where emission intensities are aggregated into indicators that are later applied to the transport performance (tonne-kilometres) of every transportation mode (Mattila & Antikainen, 2011). These models rely primarily on general factors and statistics, not being able to reflect the impacts of changes in freight flow patterns.

The existing gap between transportation demand and energy accounting methodologies, suggests the need for the development of more integrated operational tools that are capable of determining freight transport demand and thus providing analysis of systemic carbon-reducing policies (Grenzback et al., 2013; Sims et al., 2014a; Lorant Tavasszy & de Jong, 2013).

### **2.1.2.1. Single Region Input-Output Analysis**

IO analysis is a macroeconomic approach where the interactions of freight flows  $x^{mn}$  between sectors ( $m$  is a producing sector,  $n$  is a purchasing sector) are endogenously determined using business expenditure patterns. For a single region economy, the total output for any given sector  $X^m$  is expressed as:

$$X^m = \sum_n x^{mn} + Y^m \quad \forall m \quad (3-2)$$

Where  $Y^m$  is the total demand for the output of sector  $m$ .

Eq. (3-2) can be also expressed as:

$$X^m = \sum_n a^{mn} X^n + Y^m \quad \forall m \quad (3-3)$$

Where  $a^{mn}$  is a technical coefficient that represents the amount of product  $m$  required to produce one dollar of product from sector  $n$ . The set of technical coefficients define the production technology and it is assumed that it remains fixed for the period of model application. The fixed feature implies that there is no substitution between the factors of production.

The solution for the production levels vector expressed in matrix notation is:

$$X = (I - A)^{-1}Y \quad (3-4)$$

Where  $Y$  represents the vector of final demand,  $I$  is the identity matrix and  $A$  is the technical coefficients matrix. The equilibrium solution is found given that the  $(I - A)$  matrix is non-singular.

#### **2.1.2.2. Random Utility Based Multiregional Input Output (RUBMRIO) model description**

Notation

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$m$	<i>producing sector</i>
$n$	<i>purchasing sector</i>
$i, j, k = 1, 2, \dots, J$	<i>regions</i>
$X_i^m$	<i>total output of sector <math>m</math> in region <math>i</math></i>
$Y_j^m$	<i>final demand of sector <math>m</math> in region <math>j</math></i>
$a_i^{mn}$	<i>technical coefficient for production (input <math>m</math>, output <math>n</math>) in region <math>i</math></i>
$x_{ij}^m$	<i>flow in monetary units of sector <math>m</math> from region <math>i</math> to region <math>j</math></i>
$C_j^m$	<i>total consumption of commodity <math>m</math> in region <math>j</math></i>
$u_{ij}^n$	<i>utility of purchasing one monetary unit of commodity <math>n</math> in region <math>i</math> for use as input in region <math>j</math></i>
$v_{ij}^n$	<i>systematic utility of purchasing one monetary unit of commodity <math>n</math> in region <math>i</math> for use as input in region <math>j</math></i>
$b_i^n$	<i>production price of <math>n</math> in region <math>i</math></i>
$d_{ij,t}$	<i>transportation cost between regions <math>i</math> and <math>j</math> by mode <math>t</math></i>
$c_j^n$	<i>average cost of input <math>n</math> in region <math>j</math></i>
$\beta_t^n$	<i>mode choice parameters for mode <math>t</math> and sector <math>n</math></i>
$\beta_0^n$	<i>alternative specific constant for sector <math>n</math></i>
$\lambda_n$	<i>dispersion parameter for sector <math>n</math></i>

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### *Formulation*

Early practical formulations for MRIO models were derived upon the conceptualization that commodities that are produced in a region are merged into a supply pool and commodities that



are consumed are merged into a demand pool. Hence, all inter-sectoral flows can be visualized as shipments from regional supply to regional demand pools of a specific commodity (Leontief & Strout, 1963). The balance condition (3-5) requires that the total production from sector  $m$  is equal to the intermediate consumption and final demand from all regions, taking into account that a region is allowed to acquire inputs locally.

$$\sum_i x_{ij}^m = \sum_n a_j^{mn} \sum_k x_{jk}^n + Y_j^m \quad \forall j, m \quad (3-5)$$

Where  $x_{ij}^m$  represents the flow of sector  $m$  from region  $i$  to region  $j$ ,  $a_j^{mn}$  is the technical coefficient that represents the fraction of production from commodity  $m$  that is used in the production of commodity  $n$  and  $Y_j^m$  is the final demand for commodity  $m$  in region  $j$ . Trade flows were estimated upon gravity type formulations where the impedance for trade was expressed as a function of transportation costs (Leontief & Strout, 1963).

An alternative and more recent multiregional framework contemplates variations in trade coefficients through a discrete choice model. Models that have implement discrete choice formulations are known to belong to the Random Utility Based MRIO (RUBMRIO) category (Cascetta, Marzano, Papola, & Vitillo, 2013). TRANUS and MEPLAN are the most prominent software packages that have embodied the RUBMRIO approach in order to deliver transport-land use interaction models (Hunt & Simmonds, 1993). Random utility is adopted to describe the choices that different sectors follow in order to purchase their inputs in a utility maximizing, or cost minimizing, way. The implementation of random utility approaches enables the model to respond to changes in transportation costs, so that, commodity prices are updated and may induce a change in the overall trade pattern. However, new prices do not affect the final demand which is exogenous to the model. The set of equations (3-7 to 3-12) have been adapted to the

algorithm proposed initially by Hunt and Simmonds (1993); more details on the algorithm will be provided at the end of this section.

The disutility function has the following form:

$$-u_{ij}^n = b_i^n + d_{ij}^n + \varepsilon_{ij}^n \quad \forall i, j, n \quad (3-6)$$

Where  $u_{ij}^n$  is the utility of each region trading with each other region,  $b_i^n$  is the selling price of commodity  $n$  in region  $i$ ,  $d_{ij}^n$  is the transportation cost between region  $i$  and  $j$ , for commodity  $n$ . These two attributes (price and transportation costs) represent the systematic or representative part,  $v_{ij}^n$ . The term  $\varepsilon_{ij}^n$  is a random element that encompasses particular features that have not been considered in the systematic portion, together with measurement and observational errors. It can be assumed that the residuals  $\varepsilon_{ij}^n$  are random variables that follow a specific probability distribution with mean equal to 0. Different assumptions about the distribution of residuals result in different representations of the model used to describe and predict choice probabilities (M. Ben-Akiva & Lerman, 1993).

The assumption of a normal distribution leads to the formulation of a Multinomial Probit (MNP) model. Even though, this assumption is intuitively reasonable, a probit model does not have a closed form solution, since choice probability is expressed as an integral, which makes it difficult to estimate, interpret and predict. The Gumbel distribution is similar to the normal distribution and is analytically more convenient since it produces a probabilistic model that can be calculated without resorting to numerical integration (Koppelman & Bhat, 2006). In this particular case, if  $\varepsilon_{ij}^n$  are assumed to be identically and independently Gumbel distributed across alternatives and observations, then trade volume of sector  $n$  from  $i$  to  $j$  is given by:

$$x_{ij}^n = C_j^n \frac{e^{\lambda_n v_{ij}^n}}{\sum_k e^{\lambda_n v_{kj}^n}} \quad \forall i, j, n \quad (3-7)$$

Where  $\lambda_n$  is a dispersion parameter and  $v_{ij}^n$  is the systematic utility.  $C_j^n$  is the total consumption (intermediate and final) of commodity  $n$  in region  $j$ , and is given by:

$$C_j^m = \sum_n a_j^{mn} X_j^n + Y_j^m \quad \forall j, m \quad (3-8)$$

And,

$$X_i^m = \sum_j x_{ij}^m \quad \forall i, m \quad (3-9)$$

Transportation costs  $d_{ij}^n$  and final demand  $Y_j^m$  are exogenous to the model. Alternative specifications for the utility function consider origin and mode choice through a Nested Logit structure. The disutility function for the model described in this chapter (3-9) follows the same structure as the function proposed for a similar study that was based on data from the state of Texas (Kockelman et al., 2005).

$$-u_{ij}^n = b_i^n + \lambda_n \ln[\exp(\beta_{road}^n d_{ij,road}) + \exp(\beta_0^n + \beta_{rail}^n d_{ij,rail})] \quad \forall i, j, n \quad (3-10)$$

The parameters for these logit type models are estimated *a priori* upon trade observations from Commodity Flow Surveys.

The cost of input  $n$  in region  $j$ ,  $c_j^n$ , is calculated as a weighted average (across all origins) of purchase prices ( $b_i^n$ ) plus the transportation prices from region  $i$  to region  $j$ .

$$c_j^n = \frac{\sum_i x_{ij}^n (b_i^n + \ln[\exp(\beta_{road}^n d_{ij,road}) + \exp(\beta_0^n + \beta_{rail}^n d_{ij,rail})])}{\sum_i x_{ij}^n} \quad \forall j, n \quad (3-11)$$

It is assumed that the selling price of commodity  $n$  in region  $j$  is equal to the production cost, which is calculated by:

$$b_j^n = \sum_m a_j^{mn} c_j^m \quad \forall j, n \quad (3-12)$$

### Algorithm

The solution for prices and monetary flows between sectors and regions is obtained through an iterative fixed point algorithm. Zhao and Kockelman (2004) demonstrated that the algorithm converges to a unique solution. The final demands  $Y_j^m$ , technical coefficients  $a_i^{mn}$ , and transportation costs  $d_{ij,t}$ , are given exogenously. Choice coefficients  $\beta_t^n$ , and origin choice dispersion coefficients  $\lambda_n$  are estimated *a priori*. Before the iterative process begins, all  $x_{ij}^n$ ,  $b_j^n$  and  $c_j^n$  are set to zero. The utilities are then calculated, given the transportation costs and selling prices at the origins. The total output from each sector in every region,  $X_i^m$ , is also updated at this stage.

Then, total consumption  $C_j^m$  of sector  $m$  in each region is calculated as the sum of the sectors intermediate consumption and final demand. Trade flows  $x_{ij}^n$  are then distributed considering utility variations. Acquisition costs  $c_j^n$  are calculated and utilized to update new prices  $b_j^n$  for the next iteration. The convergence criteria considers that the difference between calculated flows from the last two iterations is extremely small.

### **2.1.2.3.Freight Distribution**

Friedrich et al. (2014) presented a review on micro and macro freight distribution structures, along with corresponding modelling approaches. At the micro level, transport demand is represented by commodity flows between production establishments, points of sale, consumption locations, warehouses and terminals. At this level, decisions often target supply paths with the minimum logistic costs, with some exceptions on commodities of high value or subject to perishability issues. The determination of a distribution structure involves a combination of multiple problems. This is known as the transportation-allocation problem, which is a generalization of both the classic transportation problem and the location-allocation problem (Leon Cooper, 1972).

In its most simple form, the objective of the transportation problem is to find an Origin-Destination (OD) matrix of flows that minimizes total transport costs under demand and capacity constraints. Since its origin, variations have been introduced to add constraints and cover more than one commodity type (Evans, 1983; Khurana, Adlakha, & Lev, 2018). Aside from the optimal distribution of flows, facility location problems are concerned with finding the number, location and size of the sources that will optimally supply a given set of destinations (L. Cooper, 1963). When the facilities are to be located within a continuous space, the problems are referred as “site-generating” models, in contrast to the discrete space counterpart known as “site-selection” models (Brimberg, Hansen, Mladonovic, & Salhi, 2008).

Network data is at the core of spatial decision problems, hence GIS play a significant role, especially aiding the assessment of market areas for present and future logistic centers (Macharis & Pekin, 2009). Moreover, recent approaches have complemented the GIS-based

approach with multi-criteria decision analysis (Özceylan, Erbaş, Tolon, Kabak, & Durğut, 2016).

On the spatial distribution side, data is aggregated over several geographical zones, and follow assumptions that are reasonable for flows with an interregional resolution (de Grange et al., 2010). Wilson (1971) derived a family of spatial interaction models upon the gravity model. This family of models has become the main framework for modelling aggregated distribution structures. The model form depends on additional knowledge about the interaction variables, and the distribution matrices can be estimated upon the execution of an entropy maximizing method given a set of knowledge-based constraints (Wilson, 1971). Fotheringham (1983) later acknowledged spatial-structure effects in the estimation of distance decay parameters, as interactions are often the result of a two-stage decision-making process, and proposed a new set of spatial interaction models referred as competing destination models. Fang and Tsao (1995) proposed the self-deterrent gravity formulation where the cost term takes a quadratic form in order to reflect the impact of congestion. de Grange et al. (2010) proposed a consolidated model (CM) that embraced the most important features of the aforementioned spatial interaction models. The CM form provided the most accurate trip estimations in comparison to other gravity-based formulations, and proved to be particularly useful when working with data with a high level of zone aggregation (de Grange et al., 2010).

## **2.2.Future directions for freight transportation planning**

Freight transport models have historically lacked the capability to capture behaviour-level processes that occur within different parts of the supply chain in a regional freight system. The models have traditionally assumed interactions on a zone-to-zone level, using sparse freight

movements as a proxy for shipper behavior, dismissing observations at the level of the traveler and lacking logistics elements like the use of distribution centres and handling operations (Baindur & Viegas, 2011; Moshe Ben-Akiva & de Jong, 2013). Aggregate data often fails to describe the structure underlying logistics operations because the pattern of shipments within a freight system is lost and replaced by patterns that respond differently to changes in transportation attributes (Friedrich et al., 2014). The multiregional resolution is heavily dependent on the accuracy of base year observations, making it only reasonable for short-term planning horizons (Ortúzar S & Willumsen, 2011).

Recent approaches incorporate schemes that capture the market structures and behaviour of agents involved in the freight system (Baindur & Viegas, 2011; Holmgren et al., 2012; Liedtke, 2009; V. Reis, 2014). Davydenko and Tavasszy (2013) addressed the challenge of capturing logistics aspects and proposed a model that integrates an intermediate step to the traditional four-step framework. The model uses discrete choice methods as part of a logistics chain model that determines the probability of goods being shipped directly or through intermediate distribution centres and warehouses (Davydenko & Tavasszy, 2013). Maurer (2008) developed an integrated logistics model that takes a production consumption matrix as input and transforms it into an OD matrix through the execution of a network optimization model with transportation and inventory costs as variables (Maurer, 2008). Yet, most of these studies still depend on synthetic models to enhance the mode decision making.

For long term planning, modeling future decision-making would be quite challenging and even unsuitable as market dynamics are constantly evolving and model calibration is based on surveys where users' responses are mostly concerned with the status quo: cost and transit time are prioritized over environmental considerations (De Maeyer & Pauwels, 2003). Furthermore, most models still rely on accessibility to micro-data which is often scarce. Commodity flow

surveys are costly, infrequent, and not practical because firms are often reluctant to disclose this information to clients, competitors and the public (M. E. Ben-Akiva et al., 2016; Lóránt Tavasszy & de Jong, 2014).

### ***2.2.1. Multimodal transportation planning***

Multimodal transportation planning emerged from the exercise of operations research in delivering optimal location of terminals, network design and configuration, and terminal and drayage operations (Macharis & Bontekoning, 2004). T. G. Crainic and Laporte (1997) addressed some of the main issues that have been identified within each of the decision making levels (strategic, tactic, and operational) in multimodal transportation planning. At the strategic level, the main considerations account for the design of the physical structure of the network and the corresponding logistics. These considerations involve decisions where a large amount of capital is fixed for a long term.

The concept of multimodal transportation denotes the consideration of at least two modes of transportation. The original definition evolved in complexity, new terminology has appeared in parallel with additional developments, conceptions and features (Vasco Reis, 2015). Intermodal transport is more restricted, multiple modes are allowed, however transportation involves one and only loading unit. The interpretation of a loading unit can be the source of ambiguity, as traditional views only validate the use of containers, hence, it has been suggested that intermodal transport should also be recognized for the organizational and productive characteristics of a transport service (Vasco Reis, 2015). Co-modal transport was derived upon intermodal transportation and explicitly acknowledges the use of alternative modes for increasing the efficiency and sustainability of transport systems, allowing for the integration of



passenger and freight transportation (Ronald, Yang, & Thompson, 2016). Synchromodality is the most recent conception and results from a combination between inter- and co-modal transport concepts. In other words, actors of a transport chain interact within a cooperative network, exchanging knowledge of the availability of resources, hence, enhancing for flexible planning and optimization of a transport service (Pfoser, Treiblmaier, & Schauer, 2016). Unlike intermodal transport, the configuration of the transport chain is not fixed, but is continuously adapted to the real conditions of the transport system (Vasco Reis, 2015).

The following paragraphs provide the background and evolution of the field of multimodal transportation planning. Early examples considered the selection of facilities (denoted as vertices of a network) that facilitate the optimal movement of goods throughout the network. The objective function represents the sum of fixed facility costs and transportation costs and the feasibility region is bounded by demand and capacity constraints (T. G. Crainic & Laporte, 1997). Özceylan et al. (2016) proposed an alternative approach, a GIS-based multi criteria decision-making (MCDM) model to evaluate potential locations for a freight village. The selection of a location for these facilities is crucial, as it will affect operating costs and prices from commodities within a region. Amongst the factors considered for site selection are intermodal connections, availability of space, topography, natural environment and urbanization, potential environmental impacts, labor market and access to telecommunications infrastructure. The process followed in their study entails deciding on the evaluation criteria, identifying suitable locations and decision-making. GIS is used to process geographic data and conduct spatial queries whereas MCDM provides a structure to the problem and prioritizes alternative decisions. The whole concept aims to combine geographic data with value judgments in order to provide adequate information for decision making (Özceylan et al., 2016).

Network design models are another example of strategic planning problems and can be perceived as a generalization of location models. In these problems, fixed costs are associated to the edges of a network, so that the aim is to select the edges that enable goods to flow at the lowest possible cost; the simplest version of this problem is known as the Shortest Spanning Tree Problem (SSTP), where the goal is to determine a minimal length tree that links all the vertices of an undirected graph  $G=(V,E)$ , where  $V$  is the set of vertices and  $E$  is the set of edges.

Network models can also be used to predict multi-commodity freight flows over a multimode network. This approach is generally considered to be more appropriate in order to address planning issues like the performance of a transportation system in regard to changes in infrastructure or demand. Furthermore, the network model approach allows for an interactive assessment of transportation related policies (T. G. Crainic & Laporte, 1997). Guelat, Florian, and Crainic (1990) presented a normative model for simulating freight flows of multiple products on a multimodal network. The demand for transportation is estimated using a freight demand model. Mode choice was also determined exogenously. The model is also based on the assumption that goods are transported at minimum total generalized cost, which is reasonable given circumstances where possible scenarios represent investments of large magnitudes. The base network is formed by nodes, links and modes that represent all physical movements on the available infrastructure. Links are represented as triplets  $(i,j,m)$  so that, aside from origin and destination, there is an additional parameter  $m$  for mode. The network is represented through parallel links between each node, one for each available mode, as shown in Figure 2.1.

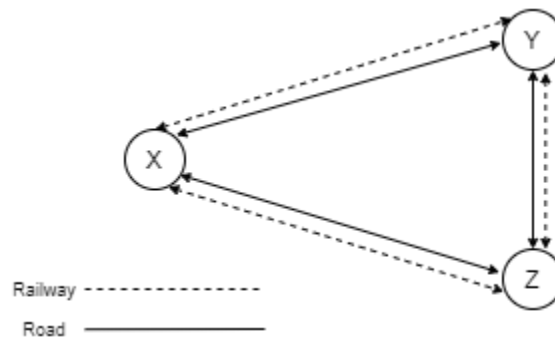


Figure 2.1: Network representation (Guelat et al., 1990)

The adoption of GIS technology has opened new possibilities and facilitated the modeling of large multimodal networks (Macharis & Bontekoning, 2004). GIS allows for a practical representation of transportation networks, traffic flows, land use patterns and potential interactions between them. Nowadays, GIS software also incorporates solvers that can deliver high quality solutions to complex network problems. Multimodal freight network planning models can exploit some of the advantages attributed to GIS. Ralston, Tharakan, & Liu (1994) reported the development of a spatial decision support system (SDSS), the Bangladesh Transportation Modelling System (BTMS). Its main purpose was to analyze transportation policies, investment choices and project the effects of changes in network structure and performance, pricing policies, supplies and demands. The network was characterized in a manner which follows the representation shown in Figure 2.1, where physical links, which are normally part of GIS, are roads and rail lines that connect nodes (e.g. towns, villages, and ports). Logical links were constructed in order to model terminal facilities so that they capture pickups, deliveries and transfers. Physical links are further divided into classes that are based on capacity and condition features. Cost and times are functions of the length of each link and the link's mode classification. Logical links are also divided into two classes: loading and unloading links, and intermodal transfers; each of these classes have specific cost functions. Trip distribution is carried out via a doubly constrained gravity model. BTMS treats

distribution modelling as a nested logit model; first, modal shares for each commodity are determined through a logit-based model. The resulting commodity-mode combinations are the input for an assignment module, so that commodities are shipped through the least disutility path by each mode. Maps obtained from official sources were digitalized into four files: polygons, nodes, links and graphic files. The node files contain information such as name ID, location and representation (supply, demand or transfer point). The link files contain information regarding mode, connecting nodes, costs and factors. The graphic files contained the geometry of the links. The GIS databases do not contain information regarding the artificial logical nodes, so that BTMS contains a module that transforms the digital representation of the network into a logical one. The model used two data structures: the GIS relational structure accessed by the mapping programs and a forward star data structure accessed by the analytical models (Ralston et al., 1994).

Loureiro & Ralston (1996) developed a Multicommodity Multimodal Network Design (MCMND) model that was formulated as a nonlinear bi-level optimization problem. The logical network generator module is based on the concepts proposed by Ralston et al., (1994). The model was designed to be used for the strategic selection of infrastructure investment strategies for intercity freight transportation networks. The investments options included the improvement and addition of new links, and the location of intermodal transshipment terminals. The upper level deliberated a mixed integer programming problem with continuous flow variables and discrete choice variables. The lower level considered a traffic assignment problem, so that commodity flows were distributed amongst a set of available paths according to a discrete choice logit model. The utility functions were based on a combination of generalized transportation costs and shipping delays. The model contemplated an interface with the TransCAD GIS-T package. The interface feature allowed users to visually evaluate the

distribution of freight flows, the addition of new links and the location of intermodal terminal facilities. The problem was solved through a heuristic two-step procedure based on column generation techniques with an embedded stochastic assignment algorithm. The column generation submodule constructed new paths (columns) between origins and destinations, so that they become potential candidates for the master problem which is based on a heuristic swapping algorithm (Loureiro & Ralston, 1996).

Jourquin, Beuthe, and Demilie (1999) presented a methodology to model bundling operations on large multimodal freight networks. The term bundling refers to the strategic consolidation of freight volumes at some nodes so that they can be aggregated and transferred to alternative modes of transportation like barges or trains. They proposed a virtual network concept which conceives the decomposition of the successive operations that are involved in multimodal transport. The virtual network is created on the basis of the geographic network and it is made up of virtual links that enable the modeling of all the operations that cannot be represented in the geographic space. This concept is embedded in a GIS software named NODUS, so that there is a set of routines that automatically generate a virtual link for each possible mode  $t$  and mean  $m$  on each real link. The problem sought to minimize an objective function that considers all the mode/means combinations and routes along with the total quantity transported, which was realized through the application of a shortest-path algorithm (Jourquin et al., 1999).

Macharis and Pekin (2009) presented the features of a location analysis model for Belgian intermodal terminals (LAMBIT) and showcased the model's capability to assess different policy measures. LAMBIT is a GIS-based model that incorporates different mode-specific network layers and the locations of intermodal terminals and municipality centres. Intermodal and unimodal road transport modes were compared in terms of market prices associated to

each. Transport prices were calculated as averages from the market prices obtained from transport companies and inland water terminals. Variable costs were applied to the network layers through a calculate function from ArcInfo. Fixed costs were defined for each node. Hence, the total price of intermodal transport was composed of transshipment costs incurred by the movement of commodities from the port to a barge or wagon, the costs of the long haul trip, transshipment costs between inland terminal and trucks and the cost of the final short haul by truck. A shortest path algorithm was used to find the routes that represent the cheapest options under distinct scenarios which follow a specific policy configuration. Studied policies includes the introduction of new terminals, an unsubsidized rail system, and subsidies on inland waterways transport (Macharis & Pekin, 2009).

J. Winebrake et al. (2008) developed a GIS-based model that integrated water, rail, and road transportation networks and intermodal transfer facilities to calculate optimal freight routes in regard to user-defined objectives. The model not only considered cost or time objectives but also was capable of accounting for energy use and environmental considerations. The model was developed in ArcGIS and used the network analysis complement to perform network optimization calculations. Furthermore, the model was based on a hub and spoke approach in order to provide a connection between given modal networks. Network spokes represented artificial connections that were conveniently created to model transfer nodes. The number of spokes on each transfer facility corresponded to the number of modes that were supported by the facility. A python-based script was developed in order to build the artificial links between modal networks and transfer facilities. Penalties were applied to links in order to integrate them into overall optimization calculations. The model calculated the shortest path between two points by testing a variety of potential alternatives and selecting the one that delivers the minimum generalized cost. Additionally, the model incorporated a Graphic User Interface

(GUI) that enabled users to modify the cost factors. A bottom-up approach was used to calculate energy use for ships, a top-down approach for trucks, and a combination of both for rail (J. Winebrake et al., 2008).

Asuncion et al. (2012) reported the development of the New Zealand Intermodal Freight Network (NZIFN) model. It is a GIS-based optimization tool that integrated road, rail and shipping networks and used deterrence parameters such as operational costs, time of delivery and energy consumption to assess the impact that hypothetical trade-offs can have over the network configuration. NZIFN followed the hub and spoke approach proposed by (J. Winebrake et al., 2008), so that artificial connections were generated between mode nodes and transfer hubs. The methodology contemplated the creation of a geospatial network. It was created from existing datasets provided by Land Information New Zealand (LINZ). The resulting network consisted of ten geospatial datasets: road network (polyline), rail network (polyline), shipping network (polyline), transfer hubs (points), road nodes (points), rail nodes (points), shipping nodes (points), road spokes (polyline), rail spokes (polyline), and shipping spokes (polyline). Distance, time, energy consumption and GHG emissions deterrence functions were assigned to all links and spokes. The model was applied on two case studies. The first case referred to the distribution of goods from Auckland to Wellington and the second was from Auckland to Christchurch. Mode shift to rail and barge was more attractive for the second case since the long distances enabled to deliver better economies of scale (Asuncion et al., 2012).

Previous studies cited in this section have been based on analytical approaches that evaluate freight systems from a central perspective, providing optimal solutions for a centralized system. In intermodal transport models, modal choice and route are predetermined with some anticipation. Synchronomodality departs from the analytical convention and accounts for

dynamic, real-time needs of freight chain actors and flexible network of services. Ambra, Caris, and Macharis (2019a) propose SYnchromodal Model for Belgian Inland Transport (SYMBIT), a computational model that simulates the modal shift potential for retail orders over a year, allowing to contrast resilience levels of static intermodal and dynamic synchromodal solutions by computing alternatives in cases of disruptions which influence service reliability. SYMBIT combines synchromodal and disruption advances as well as advances in agent-based modelling (see Section 3.4.2) to capture emergent patterns over the simulation of disruptive scenarios. Findings from their study denote potential limitations from the implementation of a synchromodal regime, as stringent time windows constraints may limit the realization of environmental benefits (Ambra et al., 2019a). Zhang and Pel (2016) also presented a comparative analysis between intermodal and synchromodal operations. The study demonstrated the use of SynchroMO (Synchromodal Modelling Operator), which consisted on four modules: demand generator, network-processor, flow assignment, and performance evaluator. The model was applied on a case study for Rotterdam hinterland container transport, and the results suggested that total system costs are comparable between intermodal and synchromodal services. However, their findings also suggest that synchromodal services can provide higher service quality and hence facilitate a modal shift from road transport (Zhang & Pel, 2016). This latter statement match the findings from Dong, Boute, McKinnon, and Verelst (2018), who argue that from a supply chain perspective, synchromodality can increase the potential for companies to make greater user on greener modes of transportation. There is a perception that a drastic shift from trucks to alternative modes will incur in negative impacts on the supply chain, especially in regards to inventory costs. Dong et al. (2018) used a case of study in Western Europe to demonstrate that synchromodality can actually shift rail share within a corridor from 30% to as much as 70%. From a supply chain perspective, a substantial shift in mode is realizable when the transportation cost reduction resulting from the increased



share of intermodal rail exceeds the corresponding inventory costs increase (Dong et al., 2018). The supply chain perspective accounts for minimal total logistic costs, which has been proposed as a better mechanism to model decision making for mode choice, as it entails other costing categories besides transport (i.e. order, consolidation, distribution, deterioration, damage during transit, and inventory costs) (Moshe Ben-Akiva & de Jong, 2013).

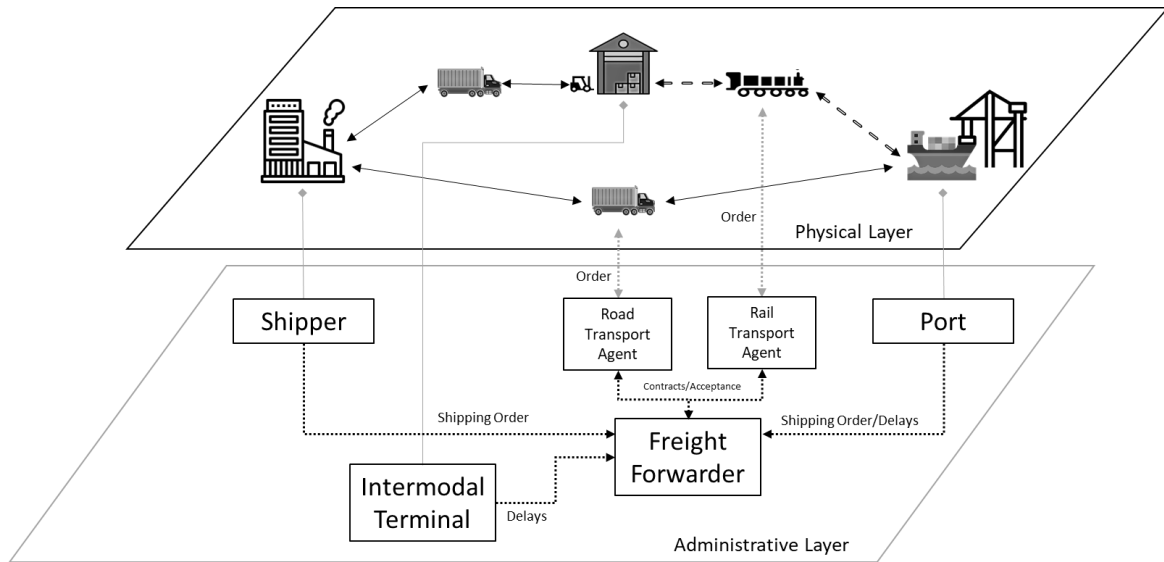
The embodiment of a synchromodal environment will likely depend on several requirements. Pfoser et al. (2016) used a critical success factor method in order to identify key enablers for synchromodality upon an extensive literature review and expert interviews. The most notable prerequisite is the generation of a network based on mutual trust and collaboration, which will likely rely on the implementation of advanced Information and Communications Technology/Information Technology Solution (ICT/ITS) technologies to dynamically provide data and optimize transport planning (Pfoser et al., 2016). Additional challenges account for the implementation of pricing mechanisms and unambiguous service agreements that can address the complexities implied by ‘mode-free’ booking regimes.

### ***2.2.2. Discrete event simulation (DES) for freight transport modelling***

The multiregional approach, described earlier in the chapter, has an aggregated nature which limits the ability to study logistics and behavior-oriented policies, and to effectively characterize the heterogeneity of actors and objects in freight chains. The adoption of simulation is emerging as a new modeling approach that has a number of advantages that effectively address some of the limitations of conventional freight transport models. Particularly Agent Based Modelling (ABM) distinguishes the different actors in transport and logistics and their corresponding roles and behavior. ABM shows the response of the transport

system given the dynamic interaction between transport actors, enabling studies of different sides of the transportation market. Furthermore, ABM enables decision makers to assess the performance and capacity of freight systems, identify bottlenecks and weigh the impact of different interventions on transport technology and infrastructure.

ABM is a simulation tool that reproduces in a virtual context the interactions and behavior of agents in a common environment. Agents are either cognitive or non-cognitive entities with specific boundaries and goals that exhibit autonomous behavior (V. Reis, 2014). Agents have responsive and communication capabilities that lead to emergent system behavior phenomena driven by dynamic interactions between them. Agents follow different behavior rules that can be based on statistically calibrated models or on decision engines where optimization takes part in the decision-making process (Liedtke, 2009). Figure 2.2 illustrates the idea of a multilayered structure in which agents in the physical layer (i.e. trucks, trains, handling equipment) respond to instructions from agents in the administrative layer. Figure 2.2 also presents different agents in the administrative layer with decision abilities, making interactions with each other upon a predefined communication system made up of contracts, messages and orders. Decisions can either be based on the implementation of auxiliary deterministic or stochastic functions.



**Figure 2.2: Conceptual structure of ABM applications on freight transport models**

ABM has not been widely used to study freight transport systems; it is still a recent approach that is building upon inherited structural components from multi-agent supply chain dynamic models. Swaminathan et al. (1998) used simulation to analyze and evaluate supply chain design and management alternatives. They studied different multi-echelon systems, aiming to deliver a modular framework that accounted for important issues and common processes in different types of supply chains. They developed a library of modeling components comprising structural elements (retailer, distribution center, manufacturer, supplier and vehicles) and control elements (e.g. information, material flow) (Swaminathan et al., 1998). Swaminathan's multi-agent framework helped to establish the foundations of recent agent-based freight models. The Transportation And Production Agent-based Simulator (TAPAS) is a freight transport model implemented in Java programming language that models production and customer demand. It also embraces the aforementioned framework through a two-tier architecture that categorizes physical entities and decision-making entities (Holmgren et al., 2012). TAPAS is based on a pull production strategy for which demand is stochastic and the number of orders follows an Economic Order of Quantity (EOQ) Model that aims to minimize

order and inventory costs (Holmgren et al., 2012). TAPAS is based on an interaction protocol where a central Transport Chain Coordinator (TCC) provides the link between Customers, Production and Transportation Agents. The TCC agent receives customer orders and finds the least-cost combination of products and transportation services. There are four instances: a plan is requested, generated, booked and confirmed. The overall sequence can be interrupted when either a production or transportation agent fails to provide a specific service. Messages are specific to each interaction and they include information on product types, quantities, pickup nodes, time windows and prices. The behavior rule for transport buyers follows a decision engine model based on a shortest-path problem (Holmgren et al., 2012).

Liedtke (2009) also proposed an agent-based approach (INTERLOG) to model freight transportation. The model allows the user to define specific microeconomic behavior to different actors. The following are relevant model assumptions: factories and wholesalers are decision maker agents, lot sizes follow minimum total logistic costs, transport rates are based on a call for bids, and exchange of information takes place in the form of virtual contracts. In INTERLOG, each simulation experiment is divided into three modules. Actors (shippers, recipients and transport companies) are geographically allocated in the *generation module*. In the *sourcing module*, the selection of potential suppliers follows a random choice function that accounts for product availability, costs, accessibility and economic activity. The parameters of the random choice function are determined by production statistics, input-output tables and truck surveys. In the *market simulation* module, flows are aggregated into shipments, forwarders are awarded with transportation contracts and truck tours are constructed. A key feature allows for the development of business relationships, agents have memory so that future decisions or choices are influenced by previous ones. Furthermore, shippers used the

transportation rates resulting from calls for bids to optimize the logistics organization (Liedtke, 2009).

Di Febbraro, Sacco, and Saeednia (2016) proposed an agent-based framework for cooperation in intermodal freight transport chains. The framework is embedded within a Discrete Event Model. Agents interact through a negotiation scheme so that decisions are bounded by local constraints and by the interaction with other agents. A novel feature of the framework is that it considers an agent that coordinates operations in the network (Network Communication Coordinator - NCC) aiming to minimize cost and maximize reliability of the entire system. The level of cooperation between actors depends on the volume of information exchanged, which corresponds to requested and proposed delivery dates. Hence, the model highlights the importance of Information and Communication Technologies and proposes a potential communication framework between actors. The global problem is decomposed into several sub-problems representing the operations of each actor, whose aim is to satisfy the requirements from other agents and maximize its local profit. The determination of the freight delivery plan is at the core of the framework. The NCC couples the sub-problems (sequence of deterministic events) and updates the freight delivery plans of the entire system. Terminal operations are defined as job scheduling problems whereas transportation operations are based on a minimum cost flow problem (Di Febbraro et al., 2016).

### ***2.2.3. The Physical Internet***

Cooperation and coordination amongst agents from different supply chains are ideas that are gaining momentum in the literature and have recently been incorporated as part of the Physical Internet (PI) concept. Montreuil, Meller, and Ballot (2012) define PI as a global logistics

system founded on physical, digital, and operational interconnectivity through encapsulation, interfaces and protocols. The aim of PI is to enable an efficient and sustainable Logistic Web, which by definition has to be of open access and with a global scope. The concept is inspired by how information is handled in the digital internet, where data is encapsulated in standard packets that can be processed by different systems. Current systems already operate with globally standardized shipping containers, parcels are standardized on smaller scales. The idea is to go beyond current practices, and the PI scheme proposes the encapsulation of physical objects into  $\pi$ -containers that shall have, amongst other features, a standard, modularized, traceable and ecofriendly design. The encapsulation feature allows the containers to interlock and to be securely attached to a carrier; furthermore, it also allows for smooth unimodal or multimodal transfers. The implementation of  $\pi$ -containers requires a major shift from private to open supply chains and logistic networks, widening the amount of logistic options available to enterprises and users throughout the global logistics network. In other words, it allows enterprises to deploy their products through a wide range of open warehouses and distribution centers, instead of restricting them to depend entirely on their own dedicated centers (Teodor Gabriel Crainic & Montreuil, 2016; Montreuil et al., 2012). Sarraj, Ballot, Pan, Hakimi, and Montreuil (2013) used a multi-agent-based simulation model to evaluate the implementation of the interconnected PI networks. The algorithm-based protocols focused on loading modular containers, finding shortest paths and consolidating containers efficiently to increase the utilization factor of the means of transportation. The simulation experiments were based on three scenario families representing a progressive shift toward a more intense use of the PI for transportation and transshipment purposes. Their study found that the PI concept could significantly improve transportation efficiency and sustainability as the combination of an open hub network and a set of modular containers lead to a significant shift to rail transportation and a 60% reduction of CO<sub>2</sub> emissions without compromising lead times or jeopardizing the

operational costs (Sarraj et al., 2013). Fazili, Venkatadri, Cyrus, and Tajbakhsh (2017) also compared the performance of a conventional logistic center against one that embraces the PI concept using the Eastern Canadian Road Network as a case of study. Their study assessed the differences in marginal value associated to different levels of consolidation. In the PI system, every node of the network is a potential center for consolidation whereas in the hybrid system, consolidation can only occur at origins, destinations and PI hubs that are strategically located. The method integrated a routing optimization framework and Monte Carlo simulation. Loads were generated randomly using Monte Carlo simulation and then the information was loaded onto the optimization framework. Their results showed a major trade-off between the total number of transshipment operations and total driving time, meaning that the success of a PI logistic system is strictly attached to the cost effectiveness of PI transit centers (Fazili et al., 2017).

The Physical Internet is now transitioning from conceptualization to actually being considered as a key element of comprehensive roadmaps for supply chain management and innovation. This is the case of the Alliance for Logistics Innovation through collaboration in Europe (ALICE), which has identified five fundamental areas of research that can potentially foster the realization of the Physical Internet (ETP-Alice, 2018). One of these areas is the existence of synchromodality, supported by corridors and hubs, providing optimal support to supply chains (Lemmens, Gijsbrechts, & Bouste, 2019). Ambra, Caris, and Macharis (2019b) presented a systematic literature review to assess and explore correlations amongst the two concepts, PI and synchromodality. It appears as the scope of synchromodal transport is currently focused on higher dimensions where containers are routed at an interregional level, whereas the PI has been confined to lower scales by addressing manufacturing processes and mostly road distribution within cities. These diverging research orientations represent opportunities, where

both concepts can be conceived as complementary approaches for the planning of more resilient and efficient transport systems (Ambra et al., 2019b).

#### ***2.2.4. Application of optimization-simulation methods for freight transportation planning***

Optimization and simulation have traditionally been considered separately but recent developments in computational power have allowed researchers to take a step further and combine them (Teodor Gabriel Crainic et al., 2018; Figueira & Almada-Lobo, 2014). There are numerous combination possibilities in regards to the hierarchical structure and purpose of the simulation (Figueira & Almada-Lobo, 2014). Within the freight and logistics domain, Caris et al. (2012) proposed a methodology to analyze the impact of cooperation amongst terminals on turnaround times and port performance. A service network design model was applied to identify opportunities for cooperation amongst terminals, that were later simulated by means of a DES model (Caris et al., 2012). Ambrosino and Sciomachen (2012) used a heuristic method to identify the best modal change nodes for a set of routes, and the best location of hubs in a transportation network. The optimization side combined plant location and shortest path problems. The analytic solution was validated by means of a DES model implemented in Witness 2008 (Ambrosino & Sciomachen, 2012). Anghinolfi, Paolucci, Sacone, and Siri (2011) proposed a heuristic procedure, in the form of a simulation optimization approach, to arrange shipping plans including routing selection, train sequences and wagon allocation. Binary and integer variables are randomly selected, and a Mixed Integer Programming solver is called on each iteration until an optimal solution is found (Anghinolfi et al., 2011). In the study of Vidović et al. (2011), a combination of a multiple-assignment-hub-network design with simulation is proposed to address the problem of optimally locating intermodal freight terminals in Serbia. The p-hub location model was used to select terminal locations from a set



of possible candidate locations, while simulation evaluated the economic, time, and environmental effects of intermodal terminal development (Vidović et al., 2011). Miller-Hooks, Zhang, and Faturechi (2012) proposed a method to deliver an optimal investment plan made of preparedness and recovery actions aiming to maximize network resilience. The method takes the form of a two stage stochastic program (integer L-shaped method) with an embedded Monte Carlo simulation module that generates scenarios based on assumed probability distributions related to disaster events (Miller-Hooks et al., 2012).

### **2.3. Summary**

Chapter 3 provides a theoretical background for the thesis. The beginning of the chapter covers state of the art modelling approaches on energy planning and transportation analysis. Long-term planning of freight systems, with strict considerations on energy demand and GHG emissions, requires an effective connection between energy and transport planning perspectives. Work presented in this thesis is aligned with a strategic planning scope where multimodality has a protagonist role in the mitigation of energy demand and carbon emissions from the transport sector. Accordingly, the chapter provided a brief review on the evolution of multimodal network planning models and on the adoption of GIS methods to enhance the virtual network concept. The limitations of conventional freight transportation models were addressed, specifically acknowledging the need for environmental considerations, data availability, the aggregated nature of flows, and lack of logistics features. The latter set of issues have inspired the adoption of simulation as part of the freight modelling toolbox. The chapter describes how simulation-based freight models evolved upon early supply chain dynamic models. The establishment of communication protocols amongst agents and the adoption of queueing theory principles have made agent-based approaches the preferred

instruments to enhance the logistic component that has been historically missing in previous freight models. Recent applications of agent-based freight models have focused on developing contract-based protocols to study the interactions of agents within the transportation market. Simulation has also been used to assess the implementation of cooperative schemes on interconnected freight transport chains.

Some of the studies addressed in this section studied agent behaviour within a transportation market and used logit-based models to enhance the mode decision-making process. For long term planning, modeling future decision behaviour would be quite challenging and even unsuitable as market dynamics are constantly evolving and model calibration is based on surveys where users' responses are mostly concerned with the status quo, which prioritizes cost and transit time over environmental considerations (De Maeyer & Pauwels, 2003). There is a research gap in the literature, since sustainability issues are still unexplored within the context of agent-based freight models and multimodal planning (Baydar, Süral, & Çelik, 2017). A similar logic can also be adopted to question claimed benefits of synchromodality over intermodality. While it is true that synchromodal operations enhance a higher level of flexibility through real-time rerouting, it appears as the level of adaptation required to mitigate energy-intensive just-on-time deliveries is not being considered as a metric for long term planning of freight systems.

The consideration of combined approaches was also discussed. Previous studies on the application of optimization and simulation methods on multimodal transportation address planning problems from the perspectives of network, drayage or terminal operators (Caris, Macharis, & Janssens, 2008; T. G. Crainic & Laporte, 1997). Evidently, there is a need for integral modelling approaches that can connect multiple perspectives, integrating management of transport services, terminal operations and infrastructure planning under a strategic scope.

Furthermore, there is a need to incorporate guidelines and opinions from transport planners, operators and policy makers into the formulation of a concept freight system that is aligned with long-term emission reduction goals.

## **Chapter 3: New Zealand as a case of study**

This chapter presents a brief review of New Zealand's freight transport and energy sectors. The chapter starts with a narrative of the evolution of freight transportation in New Zealand, addressing historical changes in behaviour, legislation and infrastructure. Current figures are covered, focusing particularly on the nexus between the transportation and energy sectors, the complexities and issues involved. The context of New Zealand is also reflected on a global scale, allowing to delineate critical trends and transformations that have turned freight transportation into an energy intensive sector.

### **3.1. Historic background of freight transportation in New Zealand**

Before the arrival of the first European settlers (Pākehā), Māori canoes that traversed rivers and coastal waterways were the main means of transport in New Zealand. Small trails also enhanced accessibility pathways between the East and West Coast. The Pākehā introduced the first horses in the early 1800's, and they became the main mean of transport for those living in the countryside. Steam driven transport was introduced by the mid-19<sup>th</sup> century. The first paddle steamers navigated the Waikato Rivers over the period 1863-1870, some actually serving during the Waikato War (Torpedo Bay Navy Museum, 2015). By the 1860's there already was a steamship service to Australia and by the end of the century, similar services provided a connection with Europe (Haworth, 2013). Numerous scattered ports and coastal settlements were characteristic to this early stage. The first colonies were located on or adjacent to low fertile lands and the coastal interconnections were essential given the irregular topography portrayed by rugged mountains corridors, dense forests and the multiplicity of rivers. The most remarkable transformation was brought by the development of railways. The

first tracks were laid in the South Island, specifically on Otago and Canterbury. In 1863, the first steam train line (11.74 km) connected Christchurch to Ferrymead (Haworth, 2013). Initially the expansion of railways was slow and road construction was also limited given the mountainous terrain, heavy rainfall and lack road materials. At this time, the economy was highly dependent on sea transport, coastal settlements were the norm with the exception of Central Otago which was a region of interest to gold prospectors.

Despite the high dispersion of seaports, only a few of them had inland connectivity to mineral resources and agricultural areas, and ended up absorbing the economic activity from neighbor ports. To cite a few examples of outstanding ports at the time we have Dunedin, Lyttelton, Wellington and Auckland, which by 1881 were handling almost eighty percent of total trade (Rimmer, 1967). A key issue to highlight from this period is that an act passed by Parliament on 1870, established a national railway gauge of 1067 mm, which until today has limited the capacity of trains to develop speedier services. Inland connectivity was provided through the development of railway penetration lines. The length of railway reached 2071 km by 1881 (Rimmer, 1967) and much of this expansion was financed through loans from Britain. The railway network was initially not interconnected but rather was a set of twelve separate sections. Penetration to hinterland was followed by a process of lateral interconnection between the major ports which led to the integration of the network. The Main Trunk line in the North Island was completed in 1908 and the rail link between Christchurch and Picton was not finished until 1945 (Haworth, 2013).

The first lorries appeared on the very limited New Zealand roads at the beginning of the 20<sup>th</sup> century. The sector started to become regulated through the Motor Car Registration Act in 1902. By 1920, cars were increasingly replacing stagecoaches and road transport was no longer localized. The consent to build national highways was supported by the Main Highways Act

that was passed in 1922. Road projects were mainly funded from vehicle registration and license fees, and from taxes on fuels and tires. The next five decades were characterized by battles over road charges and regulations. Before 1961, trucks were only allowed to travel up to 50 km. By 1977, the limit was raised to 150 km and several commodities gained the right to be exempt from the regulation (Cavana, 1997). The battle between road and rail has been a constant theme throughout the 20<sup>th</sup> century and road transport has undergone major changes leading to being largely deregulated in 1986.

On a broader context, one of the most remarkable breakthroughs for the freight sector and for the global economy was the technological disruption brought through the containerization of commodities. The trigger event that led to the container revolution took place on April 26, 1956, when the *Ideal X* tanker used predominantly for petroleum trade, departed from Newark and headed to Houston carrying 56 *tin boxes* on a modified spar deck. The innovative style of transport would grow in popularity over the next half-century, to become the standard way to move cargo across the world (Cudahy, 2006). Containerization reduced the time allocated to loading and unloading operations, leading to a drastic drop in transportation costs. From a macroeconomic perspective, containerization fostered globalized trade and connected remote markets. Before its dissemination, the exchange of raw materials and final products was predominant. It was the establishment of containerization that allowed for the exchange of intermediate products as it widened the availability of supply sources and production factors. At a micro-level, it forced the transformation of ports, where operations were automated, making them less labor intensive. It enhanced rapid intermodal coupling operations, and ships could load and unload cargo in a matter of hours instead of weeks. Factories and farms no longer required to be located near ports, but rather moved to the cheapest locations for land and resources, paving the way for complex supply chains, no longer dependent on local production

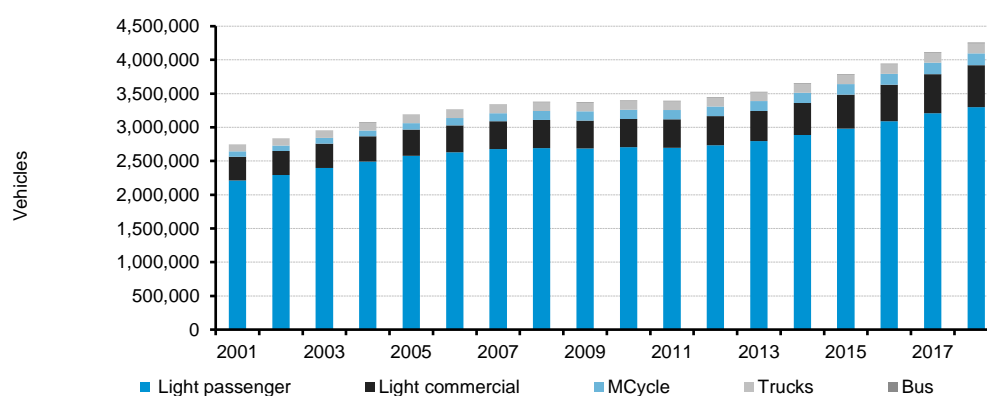
(Demil & Lecocq, 2006). On the other hand, containerization has indirectly supported trucking dominance, as container transfer operations have become versatile allowing just-in-time deliveries to become reliable. The vast expansion of the road network has overshadowed the construction of railways and opened up remote areas to commerce and development, at the expense of environmental degradation (Smil, 2017).

### **3.2.Present overview**

New Zealand is a geographically isolated island state with a population of 4.8 million. It has a characteristic geology and irregular topography owed to being located over a major geological fault line. Despite its geographical isolation, the country has managed to maintain a steady GDP growth rate of 3% in recent years. Its economy currently ranks first in the world for the ease of doing business index, reflecting on high business investment, simpler regulations for businesses and stronger protections of property rights (The World Bank Group, 2020). On the other hand, income distribution (0.32 Gini coefficient) is more unequal than the Organization for Economic Co-operation and Development (OECD) average (0.31 Gini coefficient), reflecting lower than average redistribution through taxes and transfers (OECD, 2019).

Road transportation in New Zealand relies on a network of 10,855 km of State highways and 84,150 km of local roads, mostly funded through the central government and local councils (Ministry of Transport, 2017a). The country does not have a local car manufacturing industry; it relies on imports of used and new cars from the Asian region. New Zealand has one of the highest car ownership rates in the world (~629 passenger vehicles per 1000 persons) (International Energy Agency, 2017a). Figure 3.1 shows that the car fleet has been increasing steadily during the last decade, with cars and SUVs growing most.

New Zealand's operational rail network measures 3,377 km, consisting of a spine that runs from Auckland to Invercargill. The interisland connection is provided through the Cook Strait ferry, and it spurs to Northland, Bay of Plenty, Taranaki, Hawke's Bays, and the West Coast. It provides commuter services in Auckland and Wellington. Additionally, there are three long distance passenger services: Northern Explorer (Wellington – Auckland), Coastal Pacific (Picton – Christchurch), and TranzAlpine (Christchurch – Greymouth). KiwiRail uses the remaining network for freight services (Ministry of Transport, 2017a).



**Figure 3.1:** Fleet Composition 2000-2018 (Ministry of Transport, 2018a)

The following sections provide more detail about the current state of freight transport in New Zealand and the corresponding implications on energy use and emissions.

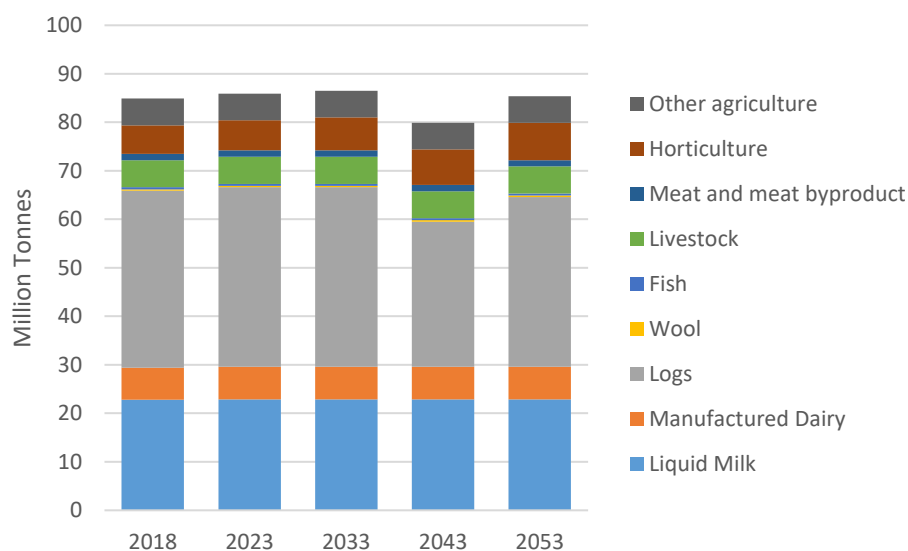
### **3.2.1. *New Zealand's freight task:***

By 2006 total freight activity was estimated to be about 26.7 billion tkm and according to the latest freight demand study the numbers had increased to 30.1 billion tkm by 2017. Road remains the dominant mode in terms of tonnes (~ 93 % share of total) and tonne-km (~77% share of total). The share of total tkm from rail has dropped from 15.6% in 2012 to 10.6% in



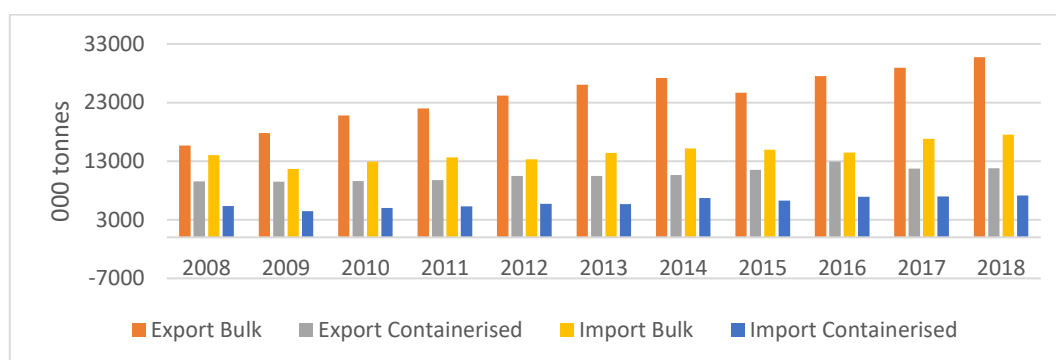
2017; most of this shift is owed to the Kaikoura earthquake which has affected the volumes travelling between islands and the reduction in coal volumes carried between Lyttelton and the West Coast (Richard Paling Consulting, Murray King & Francis Small Consulting, & EROAD Limited, 2019).

Figure 3.2 portrays the current and projected shares in tonnes for supply-driven commodities. In terms of tonnage, log transportation has the highest annual share with 36.5 million tonnes, followed by liquid milk with 22.8 million tonnes. Recent changes reflect a sharp growth in movement of milk (8%), manufactured dairy (17%), logs (25%), timber products (8%), concrete (41%) and aggregate (50%) in contrast to 2012 freight flows. Despite, recent trends, the projections are relatively conservative, with estimates of limited growth overall and even declining flows for some sectors.



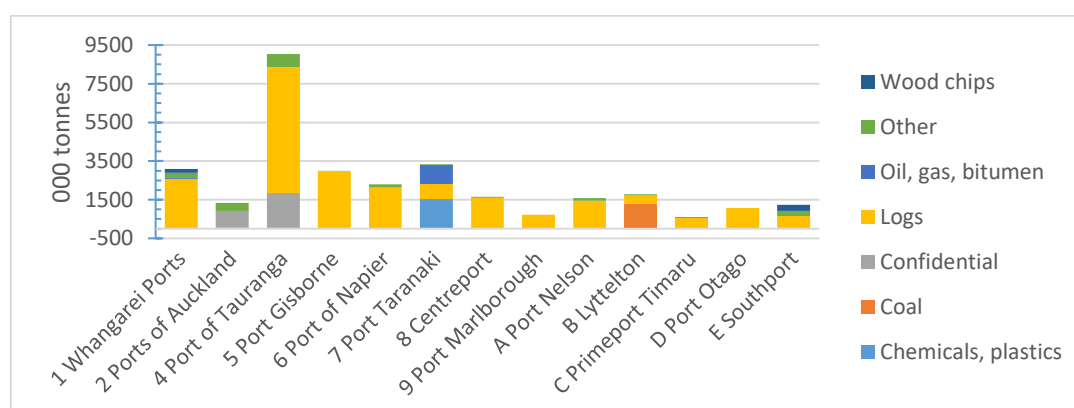
**Figure 3.2:** Movements of supply driven commodities 2017-2053 (Richard Paling Consulting et al., 2019)

According to official figures from the Ministry of Transport, 42.5 million tonnes were exported from New Zealand by sea in the year 2018 (Ministry of Transport, 2018c). Figure 3.3 shows that bulk exports have been increasing at an average annual rate of 7.1%, unlike volumes for the remaining categories which have remained stable during the past decade.

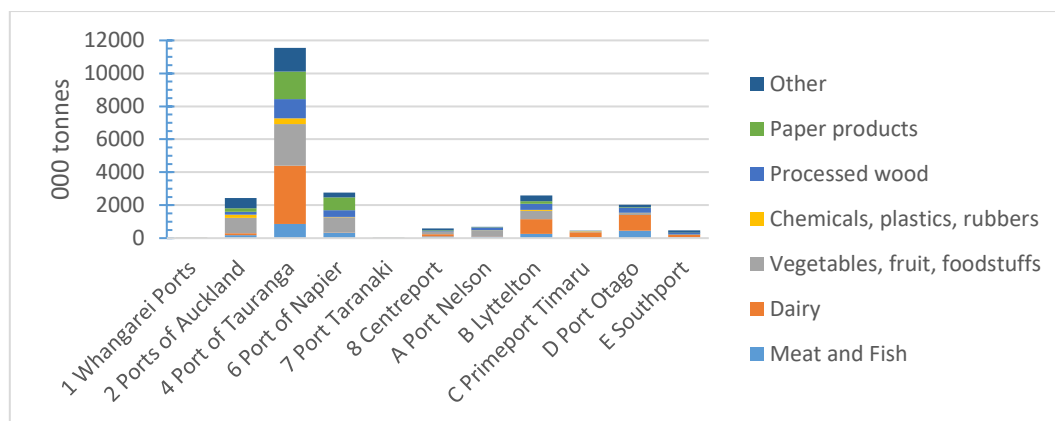


**Figure 3.3:** New Zealand's Imports and Exports by Sea 2008-2018 (Ministry of Transport, 2018c)

In accordance with Figure 3.4, bulk exports have a 72.2% share of total exports, mostly made up by logs from the forestry sector, whose activity is mainly concentrated in the North Island. As for container exports, Figure 3.5 shows that dairy, wood products, paper products, vegetables, fruits and foodstuffs are the most relevant sectors.

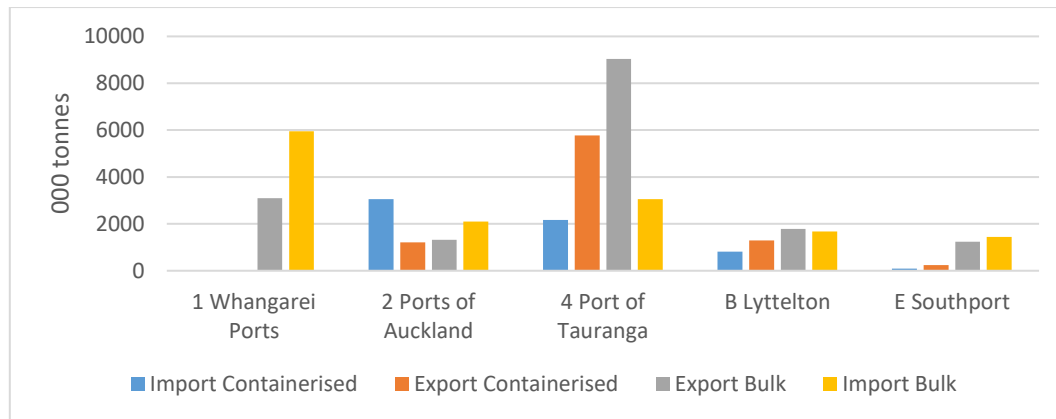


**Figure 3.4:** New Zealand's Bulk Exports by Sea 2018 (Ministry of Transport, 2018c)



**Figure 3.5:** New Zealand’s Container Exports by Sea 2018 (Ministry of Transport, 2018c)

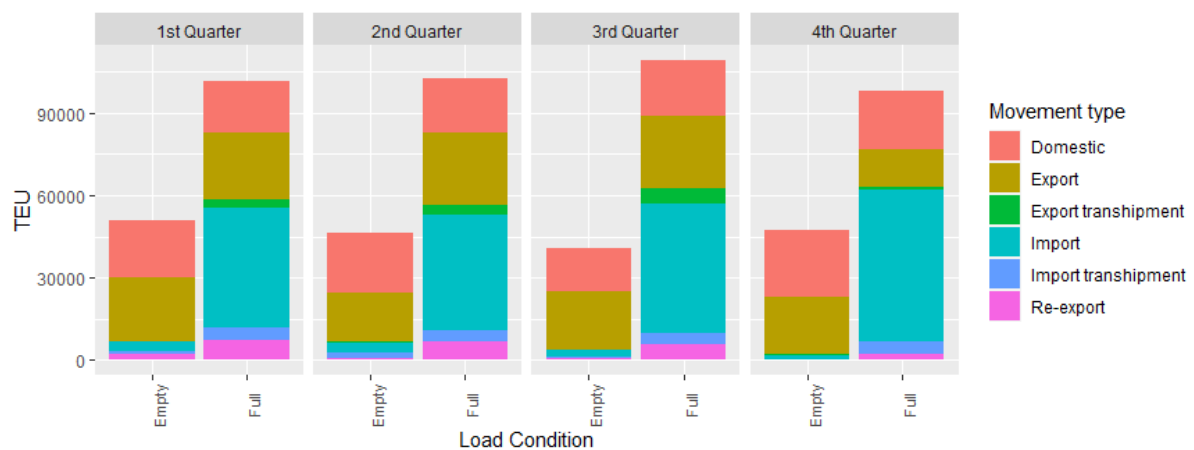
Figure 3.6 contrasts import and export volumes for the main ports in New Zealand, where Port of Tauranga (POT) appears as a strategic cornerstone for international trade. Furthermore, there is a novel distinction between Ports of Auckland (POA) and POT, POA being specialized on container imports, but have managed to balance the flows through operations at inland terminals like MetroPort. Shipping lines contracted to use MetroPort Auckland call at the POT where import cargo destined for Auckland is offloaded at the Tauranga Container Terminal. Cargo is then railed to MetroPort Auckland before distribution to its final destination. The same process happens in reverse for Auckland sourced export cargo (Port of Tauranga, 2015). Lyttelton Port Company (LPC) works under a similar scheme, as it counts with two inland hubs for receiving, storing and consolidating containers and as a distribution points where containers are transferred between trucks and trains. Rail connection with the port improves container freight efficiency, and decreases travel time and freight costs for customers. It also alleviates road congestion by removing a significant number of trucks on the port route (Lyttelton Port Company, 2019). Inland hubs are becoming strategic centers for repositioning empty containers.



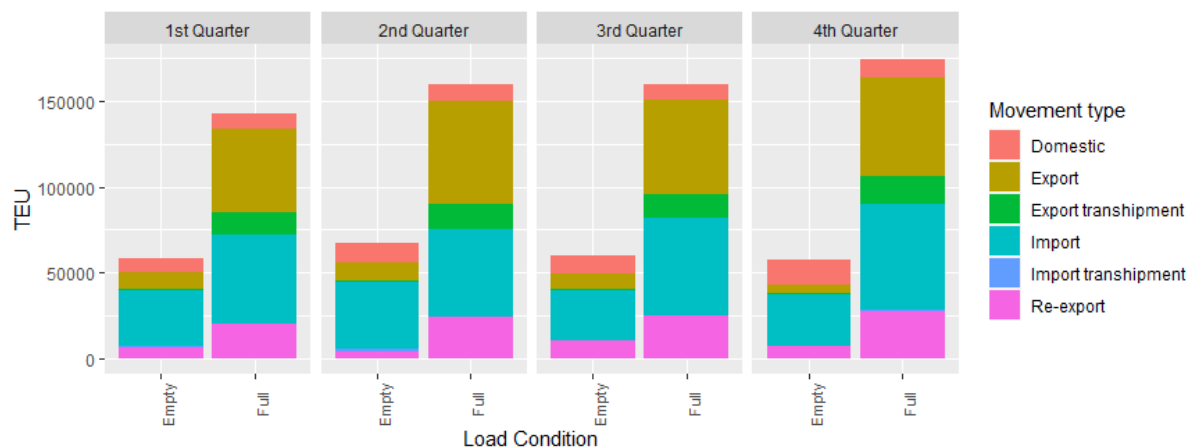
**Figure 3.6:** Imports and Exports for New Zealand’s main ports 2018 (Ministry of Transport, 2018c)

The repositioning of empty containers is one of the most complex problems concerning global freight distribution. The major causes include trade imbalances and also repositioning costs, container manufacturing, and leasing costs and usage preferences (Notteboom & Rodrigue, 2008). Figure 3.7, Figure 3.8, and Figure 3.9 provide a closer look at quarterly international traffic (Import, Export, Re-export) and coastal movements (export transshipment, import transshipment, domestic in and domestic out) for some of New Zealand’s main ports. Export transshipment refers to a container loaded at a local port and then shipped to second local port for export, whereas an import transshipment refers to a container that arrives from overseas and then loaded onto another ship to be delivered to a second local port. Re-export refers to containers that arrive from overseas and are loaded onto a second ship to be exported back to a destination overseas. Figure 3.7 confirms that there is an evident misbalance of container flows at POA, imports are predominant, it is a gateway to other local ports with significant number of domestic exchanges and there is a considerable amount of empty containers being exported on a quarterly basis, approximately 20000 Twenty-Foot Equivalent Units (TEU). Figure 3.8 shows that POT copes with a higher number of containers, has managed to balance imports with exports, and appears as a strategic connection for international movements with

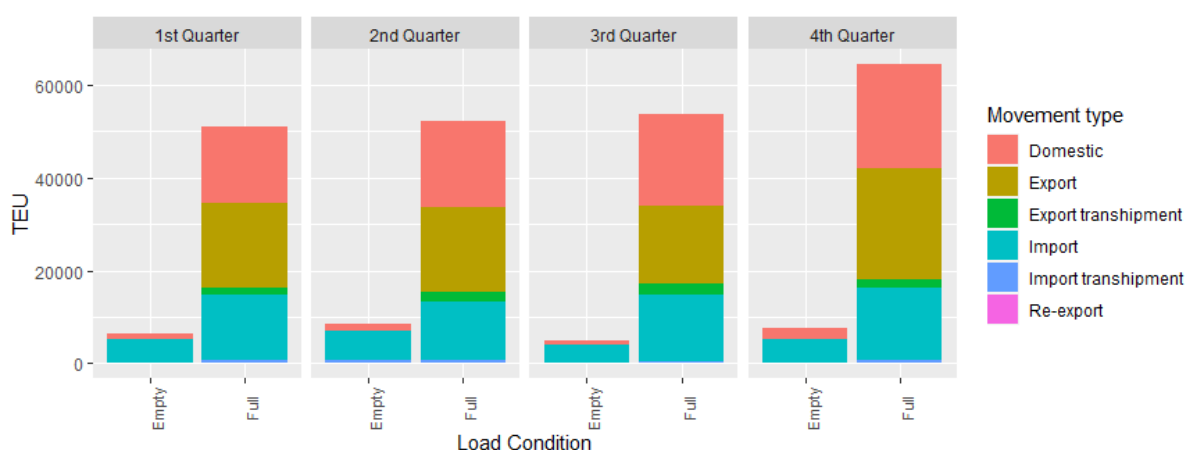
a relatively high number of quarterly re-exports (~25000 TEU). Moreover, there is a considerable number of empty container arrivals. As for LPC, Figure 3.9 shows that there is a misbalance between exports and imports, but unlike POA, exports are predominant in this case. Generally, there is a pattern for all three ports, evidencing higher number of exchanges during the last quarter.



**Figure 3.7:** Ports of Auckland Quarterly Container Traffic 2018 (Ministry of Transport, 2018c)



**Figure 3.8:** Port of Tauranga Quarterly Container Traffic 2018 (Ministry of Transport, 2018c)



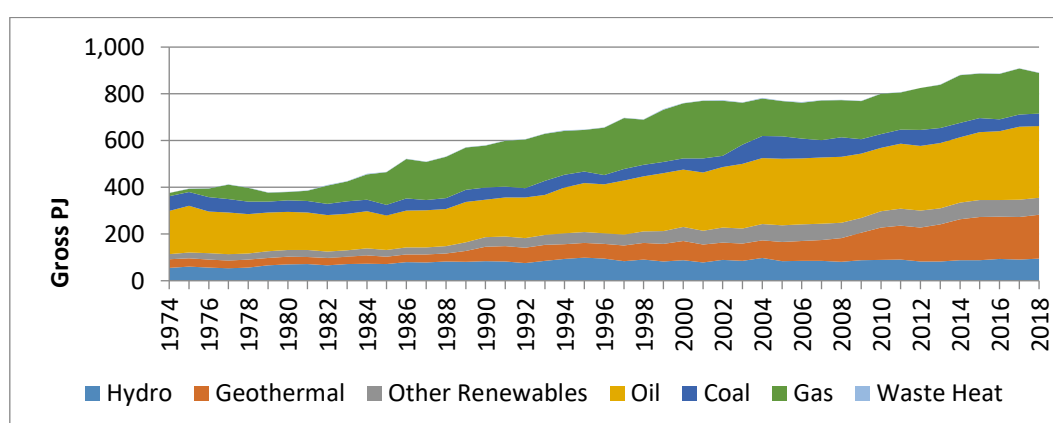
**Figure 3.9:** Lyttelton Port Quarterly Container Traffic 2018 (Ministry of Transport, 2018c)

### 3.2.2. *New Zealand's energy sector:*

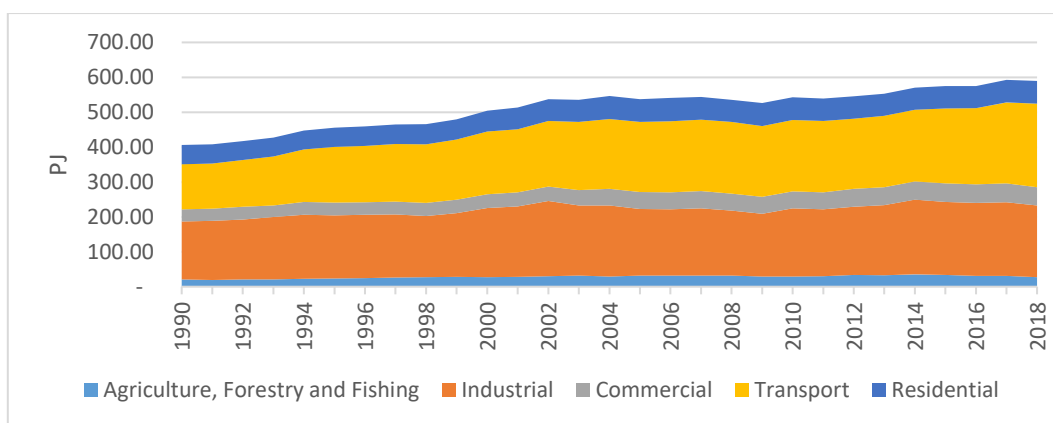
New Zealand has a rich resource base of renewable and non-renewable sources. The country exports high quality oil (58.44 PJ in 2018) and imports cheaper foreign oil (380.58 PJ in 2018) that is refined locally, making the country a net oil importer. It exports high-quality coking coal (38.52 PJ in 2018) mainly from the West Coast in the South Island, only 13.82 PJ of coal were imported in 2018. The country covers all of its natural gas requirements through indigenous production (172.25 PJ in 2018), without exchange with other countries. The contribution of fossil fuels to the economy is currently on decline, as international fossil-fuel prices are relatively low and have degraded the attractiveness of new investments. Simultaneously, the participation of renewable energy in power generation is high and expected to increase in the future, mainly through the addition of wind power capacity. The contribution of renewable generation to Total Primary Energy Supply (TPES) was 355 PJ in 2018. Figure 3.10 shows that hydro and geothermal together provided 32% of TPES in 2018, particularly the contribution of geothermal has increased by 84% during the last decade, making New Zealand the country with the highest geothermal share in TPES. Energy self-sufficiency is the

indigenous production share of primary energy supply. New Zealand is considered as a stable country in terms of energy security given a self-sufficiency of 75.4% in 2018. Nevertheless, self-sufficiency has been on a decline trend that is mainly owed to a recent drop in indigenous production of oil (33% over the last decade), while the local demand for oil has slightly increased (Ministry of Business Innovation and Employment, 2019).

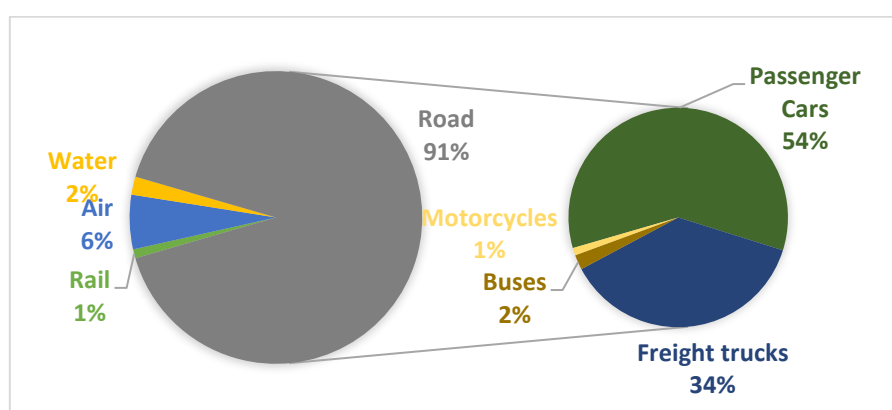
New Zealand's total consumer energy reached 592.71 PJ in 2017, marking a historic peak in demand. Transport with a 41% share of total consumption is the sector with highest energy demand, followed by Industry (35%), Residential (11%), Commercial (9%) and other sectors (5%). Figure 3.11 shows sector specific series of consumer energy for the period between 1990 and 2018. Most of the recent increase in demand is owed to the transportation sector. Figure 3.12 shows the share of transport energy demand by subsector, where road transportation has the highest share (91% share of transport energy demand), reflecting on the expansion of the national vehicle fleet shown in Figure 3.1. Moreover, freight trucking is a sector with high energy use, only being surpassed by passenger cars. This reflects on the previous discussion in Section 3.2.1 on trucks dominance over other modes of transportation.



**Figure 3.10:** Total Primary Energy Supply y Fuel 1974 – 2018 (Ministry of Business Innovation and Employment, 2019)



**Figure 3.11:** Total Consumer Energy 1990 – 2018 (Ministry of Business Innovation and Employment, 2019)



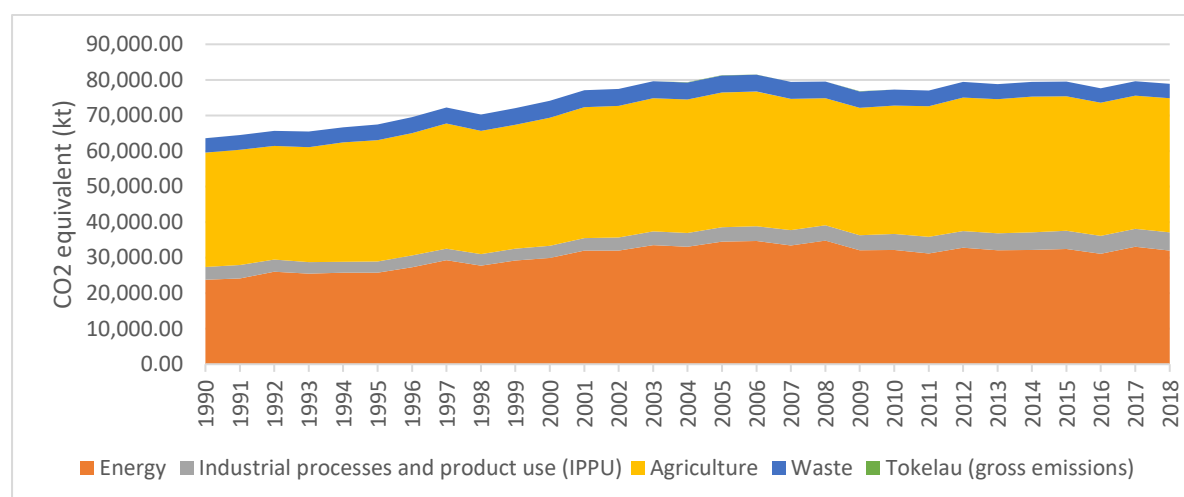
**Figure 3.12:** Transport Energy by subsector (International Energy Agency, 2017a)

According to the latest energy balance (base year 2018), 99.9% of the transport sector's energy needs are fulfilled by fossil fuels, specifically 91% being diesel and petrol (Ministry of Business Innovation and Employment, 2019). High dependency on fossil fuels represents a major risk for the transport sector, for the economy, and for the environment. A recent report published by the IPCC, indicates that if the global mean surface temperature keeps increasing at the current rate, it is likely (66% to a 100% probability) that the planet will reach a 1.5 °C increase as soon as by 2030 (Intergovernmental Panel on Climate Change, 2018). The report portrays the urgency to strengthen the global response to the numerous implications (sea level



rise, impacts on biodiversity, ocean acidification, risks on economic growth, amongst others) of a 1.5 °C warming. In response to this, New Zealand has ratified its commitments under the Paris Agreement, to reduce GHG emissions by 30 per cent below 2005 levels by 2030. A long term target is contemplated under the recent Climate Change Response (Zero Carbon) Amendment Act. Following recommendations of Paris Agreement, it repeals the former domestic 2050 target, and requires that net accounting emissions of GHG in a calendar year, other than biogenic methane, are zero by the calendar year beginning on 1 January 2050 and for each subsequent year. The Zero Carbon Act also specifies that the target is subject to modification given significant changes in: global action, scientific understanding of climate change, economic circumstances, technological developments, amongst others (Ministry for the Environment, 2019). It is worth to highlight that the long term target specifies net emissions, which consider potential removals from the sequestration of carbon that occurs due to plant growth and increases in the size of the harvested wood products pool. Looking at historic series shown in Figure 3.13, it is evident that Energy and Agriculture are the main contributors to national GHG emissions. The contribution of agriculture is mostly made up of biogenic methane emissions (74.1 per cent of the sector's emissions), which are considered under a complementary target. This leaves out the energy sector where Transport is responsible for 16,624.7 kt CO<sub>2</sub>-e annual GHG emissions (52.0 per cent of emissions from the Energy sector), or 21.1 per cent of gross national emissions; road transport accounted for 15,070.9 kt CO<sub>2</sub>-e (90.7 per cent) of total transport emissions (Ministry for the Environment, 2018). New Zealand appears well suited to enhance the electrification of transportation, with a high share of renewable power generation (~80%). The New Zealand Government has already announced a set of measures (including: exemptions on road user charges, information campaigns, innovation programs) particularly aiming to enhance the uptake of electric vehicles (Ministry of Transport, 2018b). However, advancement towards low carbon transportation systems will

not only depend on technological progress but also on behavioural changes and major investments in infrastructure to enhance a substantial shift to more energy efficient modes of transport, being this last category one of the main motivations for this thesis.



**Figure 3.13:** Annual GHG Gross Emissions by sector (Ministry for the Environment, 2018)

### 3.3. Summary

Chapter 3 started with a brief historic background of freight transportation in New Zealand, highlighting the major events and technological developments that led to the current dominance of truck transportation. Oil's high energy return on investment, containerization, the expansion of the road network, and the deregulation of trucking have either directly or indirectly enhanced a trade-off between energy security and just-on-time door to door deliveries.

New Zealand has seen a period of economic stability and in contrast to other countries it performs relatively well in terms of employment rates, health and social support. The geographic isolation has not stopped the country from achieving energy sovereignty due to its vast resource base of primary energy resources. New Zealand is one of the countries with the

largest share of renewable electricity (approximately 80%), and the government is expecting to expand it to 90% by 2025. Despite the contribution of power generation from renewable sources, the country is highly dependent on the use of oil, natural gas and coal, as its economy is strongly backed up by energy intensive industries and agriculture. Moreover, the reliance on oil places the transport system at risk given the implication of an increasing trend in imports of second hand vehicles from overseas and the degradation of railway infrastructure.

In response to its commitments towards the Kyoto Protocol and Paris Agreement, the country has established two sets of targets, for the mid and long terms, labelled as international and domestic, respectively. The domestic long term targets, consider a specific category for biogenic methane emissions; all other GHG are expected to reach net zero emissions for 2050. Despite the widespread consensus on the urgency on keeping GHG atmospheric concentration below 450 ppm, there is still a bit of ambiguity and uncertainty on reporting methodologies, specifically on the inclusion of Land Use, Land Use Change and Forestry (LULUCF). The Zero Carbon Act allows to account for carbon sequestration from LULUCF, meaning that, a 70% reduction of current gross emissions is needed by 2050, assuming that forests and forest soils keep their current potential for terrestrial carbon sequestration.

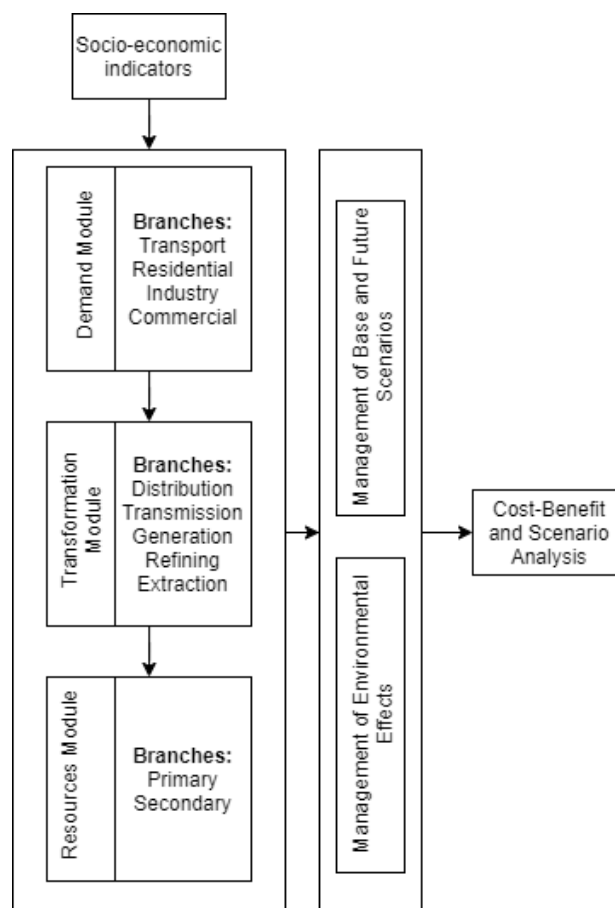
## **Chapter 4: Energy and Environmental Planning Model**

The interaction between transport and energy systems has been studied through the implementation of energy and environmental planning models, some examples and applications were cited on Chapter 2. This chapter reports the development of a Long Range Energy Alternatives Planning (LEAP) model along with a brief demonstration of a scenario based analysis of the country's potential energy and transport outlook for the future. LEAP counts on a large database of emission factors and can also be used to run cost benefit analysis using simulation and optimization (Stockholm Environment Institute, 2017). LEAP is widely used by researchers, consultancies, and policy makers worldwide and it has proven useful in assessing energy and environmental policy interventions on the transport sector. The development of the model illustrates the chain of connections and dependencies between energy resources and points of consumption for different sectors including transportation. This chapter covers a description of the model structure, data sources and validation. From a supply chain perspective, a substantial reduction in GHG emissions could be achieved by means of different measures in the broader supply chain including: shift to greener modes, changes in vehicle technologies, substitution of energy carriers, relaxation of just-in-time deliveries and low carbon sourcing (L. Tavasszy & J. Van Meijeren, 2011). Accordingly, a brief scenario based analysis focuses on techno-economical feasible pathways and considers the alternatives that require a whole-system approach assessment, as current integrated models do not contain a detailed representation of infrastructural and behavioural changes (Sims et al., 2014b). This thesis is concerned on the potential of multimodal transportation as a carbon reducing strategy. There seems to be a high level of optimism around the future role of multimodality, for instance, one of the goals of a recent White Paper from the European Commission is that more than 50% of road freight transport over 300 km should shift to other modes such as rail or

waterborne transport by 2050 (L. a. Tavasszy & J. van Meijeren, 2011). This thesis is also concerned on assessing the mechanisms by which an ambitious modal shift can be realized in the New Zealand context. Scenarios in this chapter account for impacts of changes in modal share, freight activity, and technology substitution on energy use and GHG emissions in New Zealand. The results from the scenario based analysis suggest the need to integrate different strategies, as a substantial reduction in carbon emissions will not only be driven by feasible technological developments but, to a great extent, will depend on changes in behavior. The model reported in this chapter is used throughout this thesis to quantify energy use, energy system costs and corresponding direct and indirect GHG emissions. Specifically, the model is used as an emissions calculator within STRATCODE, as will be described later in Chapter 6.

#### **4.1. Model setup and data**

In this chapter LEAP is used to build a model of the Energy System in New Zealand and to explore the implications of changes in freight activity, modal share and technology substitution. LEAP's structure follows a hierarchical form that combines several modules (Demand, Transformation, Resources), as is shown in Figure 4.1.



**Figure 4.1:** The Structure of LEAP’s calculations (Stockholm Environment Institute, 2017)

The sources of information and fundamental assumptions are described in this section. The year 2018 was selected as the base year in concordance with the most recent data reported by official sources. The demand module was organized into four subfolders for the Transport, Industry, Commercial, and Residential sectors, respectively. The transport module had a higher level of detail as our study particularly focused on the impact of policy on energy consumption and GHG emissions from this sector. The first level of disaggregation considered passenger and freight subfolders. VKT and vehicle occupancy were used to calculate passenger kilometers (PKMs) that were further allocated to the household light, motorcycle, heavy bus and light commercial sub-categories. VKTs from heavy trucks were excluded from the road passenger category, as they were accounted for in terms of Tonne Kilometers (TKM) within

the road freight category. Fuel consumed by cruise liners and other ferries were not accounted for within the passenger category. The Freight subfolder is entirely based on transport activity and modal shares (i.e. road, rail and coastal shipping) reported on the National Freight Demand Study (Richard Paling Consulting et al., 2019). Fuels used within the passenger and freight categories include Diesel, Petrol, Electricity, Residual Fuel Oil and Jet Kerosene. Other fuels like LPG were not included in the analysis, as they are not representative within the New Zealand transport sector (approximately 0.4% share). Data used within the transportation branch along with the corresponding sources are summarized in Table 4.1.

**Table 4.1:** Transport Data and Sources

<b>Description</b>	<b>Sources</b>
VKTs by vehicle and fuel type	Annual vehicle fleet statistics report (Ministry of Transport, 2018a)
Vehicle occupancy	Transport Indicators (Ministry of Transport, 2018e)
Aircraft PKM	Air travel statistics and modeling (Cross & Wang, 2014)
Rail passenger activity	Transport Indicators (Ministry of Transport, 2018e)
Freight activity and modal shares	National Freight Demand Study (Richard Paling Consulting et al., 2019)
Energy intensities	Lipasto Traffic Emissions (Tiwari & Gulati, 2013; V. T. T. Technical Research Centre of Finland Ltd, 2017)

In the Transport Branch, energy intensities were specific to each technology. The definition of Industry, Commercial and Residential sectors followed a different approach. Aggregate energy intensities were defined at the top level of each of these categories. Each category contains a set of fuel branches, and a share was assigned to each one of them. Sectoral Energy Intensities were expressed in terms of energy use per unit of gross product. Data on GDP breakdown by

industry for New Zealand was obtained from Figure.NZ (figure.NZ, 2016). Sectoral energy use, fuel shares and installed power capacities were obtained from online documentation on energy statistics published by the Ministry of Business, Innovation and Employment (MBIE) (Ministry of Business Innovation and Employment, 2015). Electricity consumption profiles for industry, commercial and residential sectors were taken from an online dataset containing half-hourly readings of electricity consumption (Electricity Market Information, 2018).

**Table 4.2:** Cost and technical data of electricity generation

<b>Technology</b>	<b>Capital cost (NZD/kW)</b>	<b>Fixed O&amp;M (NZD/kW)</b>	<b>Variable O&amp;M (NZD/MWh)</b>	<b>Process efficiency (%)</b>	<b>Availability (%)</b>	<b>Lifetime (Years)</b>
<b>Hydroelectric</b>	4395.30	6.73	33.18	100	Variable	50
<b>Onshore Wind</b>	2601.90	54.83	21.30	100	Variable	20
<b>Geothermal</b>	5909.40	102.84	16.63	15	Variable	30
<b>Thermal Coal</b>	3924.90	60.92	10.04	38	95	30
<b>Thermal Natural Gas</b>	1177.47	21.14	12.52	35	95	30
<b>Thermal Diesel</b>	970.20	15.29	9.69	40	95	20
<b>Cogeneration NG</b>	1969.80	34.40	10.85	40	95	30
<b>Cogeneration Wood</b>	2822.40	38.15	10.85	24	50	30
<b>Thermal Biogas</b>	6468.00	29.40	76.63	40	50	30
<b>Solar PV</b>	5189.10	68.41	19.45	100	30	30

Energy Transmission and distribution, Electricity Generation, Oil Refining, Natural Gas extraction and Oil Extraction define the transformation module. In regards to the Electricity Generation branch, the model incorporates “availability shapes” to describe the fraction of time a plant is available in each of the time slices considered in the analysis. These profiles were



derived from monthly datasets containing half-hourly readings for different power plants in New Zealand (Electricity Market Information, 2018). Remaining data on costs and technical features for electricity generation were obtained from official reports and scientific literature (Dagher & Ruble, 2011; Electricity Authority, 2014; Kachoei, Salimi, & Amidpour, 2018; Kale & Pohekar, 2014; Ministry of Business Innovation and Employment, 2016; Organisation for Economic Co-operation and Development, International Energy Agency, & Nuclear Energy Agency, 2015; Park, Yun, & Jeon, 2013). Table 4.2 provides a summary of data entered in the electricity generation branch. Annual summary statistics from the MBIE website were used to define the losses, historical energy production, exogenous capacity, and availabilities within the Oil Extraction, Natural Gas Extraction, Oil Refining, Transmission and Distribution branches (Ministry of Business Innovation and Employment, 2015).

#### **4.2. Model validation:**

The model was validated by means of comparison against official ciphers. The model estimates 34.1 million tonnes CO<sub>2-e</sub> total GHG emissions from the energy sector, approximately a 7% difference from the 31.9 million tonnes CO<sub>2-e</sub> reported in the national greenhouse gas inventory (Ministry for the Environment, 2018). To a certain extent the difference is owed to the omission of fuel use for international transportation, which according to inventory estimates is approximately 4.9 million tonnes CO<sub>2-e</sub>. Also, the estimated TPES was 861.9 PJ, approximately a 3% difference from the 890.68 PJ reported in the energy balance. **Figure 4.2** pictures the energy balance according to our modelling approach. It follows the overview presented in Chapter 3, with transport and industry as the main energy users. Geothermal, crude oil and natural gas sources are the main contributors to TPES. The model calculates 250.5 GJ in extraction, transformation and distribution losses, 30% of TPES.

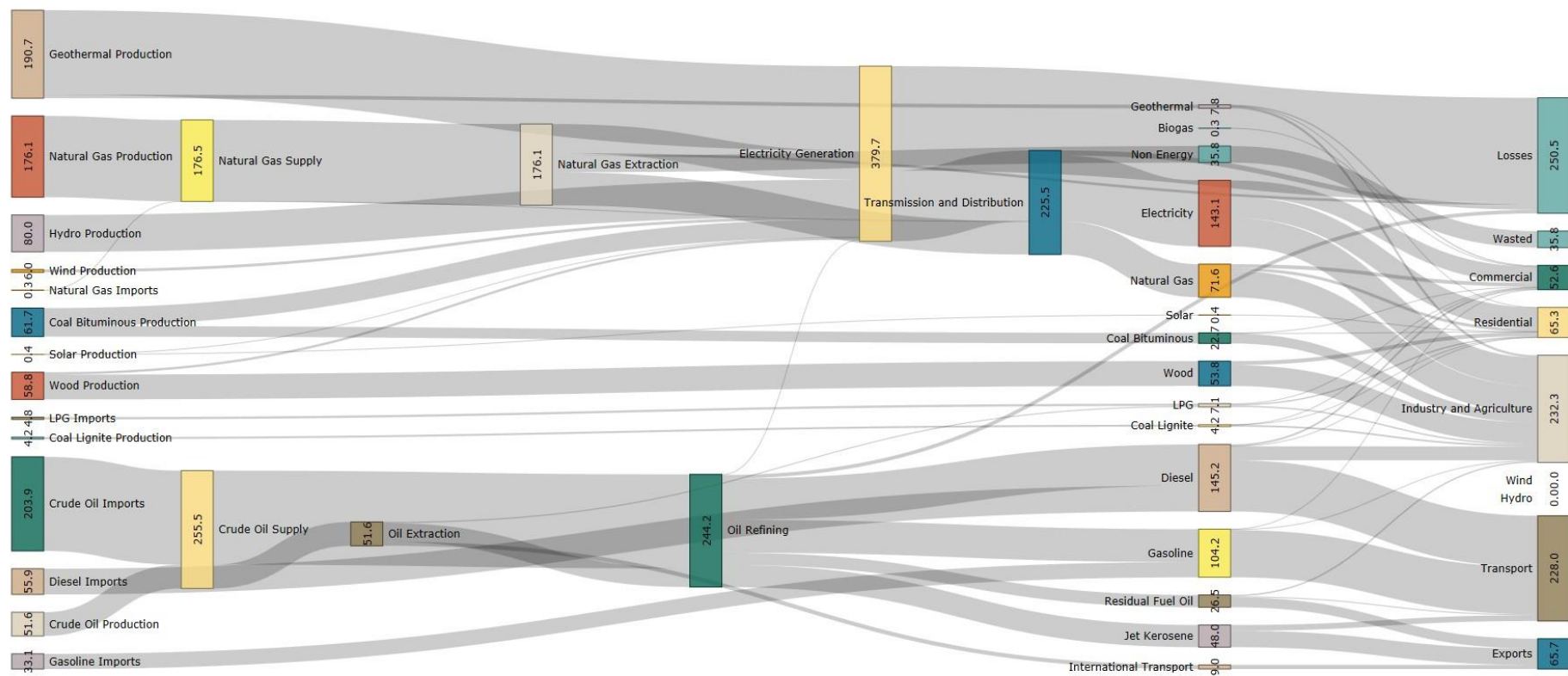


Figure 4.2: Energy Balance from New Zealand LEAP model

### 4.3.Scenarios:

Official sources project an increase in freight tonnages, and a stable market share for different modes. Projections have not considered policies or investments supporting shifts to more efficient freight transport modes (Ministry of Transport, 2017b). This section provides a brief demonstration of a LEAP model in the form a scenario based analysis that evaluates mitigation pathways that may have been overlooked. Aside the Business as Usual (BAU), four scenarios are defined by hypothetical changes in freight activity, modal share, and technology substitution. Table 4.3 shows the corresponding codes and descriptions.

**Table 4.3:** Scenario denomination

Code	Description
<b>BAU</b>	Business as usual
<b>SC1</b>	Reduction in transport activity
<b>SC2</b>	Modal shift to rail
<b>SC3</b>	Electrification of railway routes
<b>SC4</b>	Combination of multiple measures

The BAU scenario follows the projections of the latest National Freight Demand Study (NFDS). The first scenario (SC1) investigates the impact of a reduction in transport activity from the movement of imported vehicles, logs and livestock. Following assumptions from the NFDS, SC1 assumes a potential reduction of 7.1 million tonnes in logging traffic. Data on livestock movements are collected confidentially under the National Animal Identification and Tracing (NAIT) scheme. Figure 4.3 is built upon this data and shows monthly movements of livestock across different regions in New Zealand. The nature of movement is not specified,

however, there is a noticeable trend of increasing numbers during the winter months and it is assumed that these numbers correspond to winter grazing practices. Scenario 1 (SC1) assumes a potential reduction of 0.8 million tonnes of traffic associated to winter grazing. In regards to modal share, it is estimated that between 2012 and 2017, rail's tkm share dropped 5%. The second scenario (SC2) contemplates an increase in rail share, in order to quantify the contribution that railways had a few years back. Rail modal share is not even across all the network, it is significant in the following routes: Auckland to Bay of Plenty (613,000 tonnes), Waikato to Bay of Plenty (693,000 tonnes – mostly exports of dairy products and logs), and within Canterbury (295,000 tonnes – mostly dairy product exports) (Deloitte, Richard Paling Consulting, Murray King & Francis Small Consulting, & Cooper Associates, 2014). Figure 4.4 displays the aforementioned routes and the third scenario (SC3) looks at the impact of having electric trains running through these routes. The fourth scenario (SC4) represents a combination of all mitigation strategies.

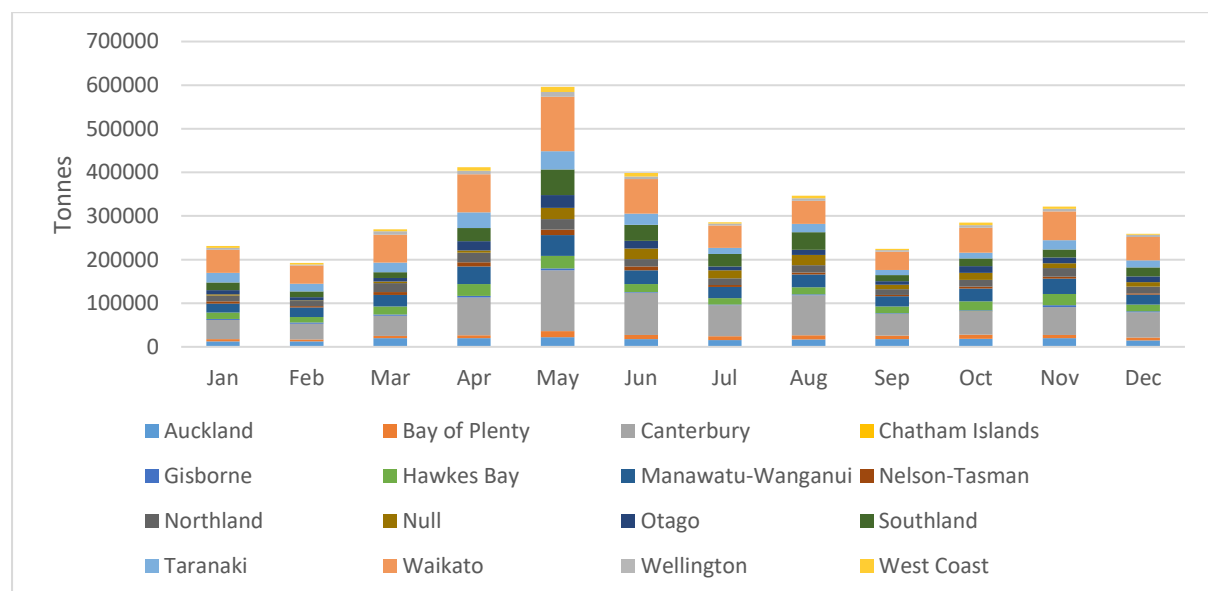


Figure 4.3: Livestock movements across New Zealand in 2018 (Ministry of Transport, 2018d)

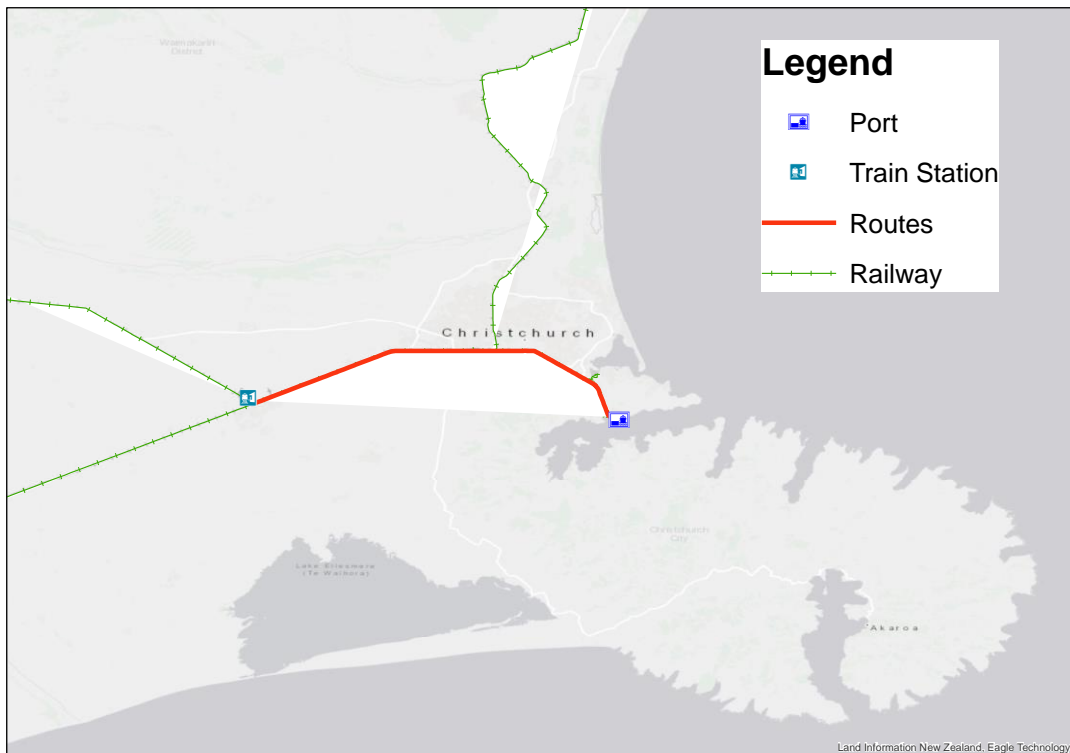
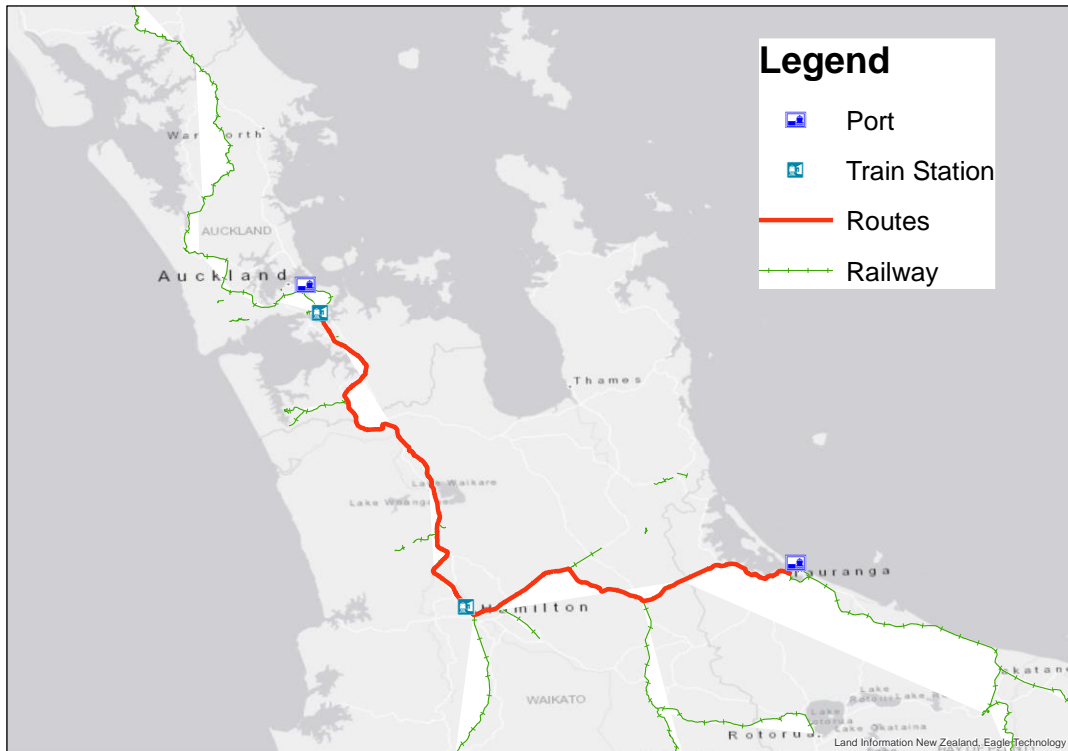


Figure 4.4: Railway routes with high traffic

## 4.4.Results and Discussion:

**Table 4.4:** Freight Sector's Energy Demand and GHG Emissions for all Scenarios in End Year

Code	Description	Energy Demand (PJ)					Total Emissions (000 tonnes CO <sub>2e</sub> )				
		Rd.	Rl.	Ct.	Σ	Δ (%)	Rd.	Rl.	Ct.	Σ	Δ (%)
BAU	Business as Usual	58.1	1.7	2	61.8	NA	4,302.7	123.3	154.3	4580.3	NA
SC1	Drop Freight Activity	56	1.6	1.9	59.5	3.7	4,149.4	118.9	148.8	4417.1	3.6
SC2	+5% Rail Modal Share	53.4	2.4	2.2	58	6.1	3,961.4	181.2	166.4	4309	5.9
SC3	Rail Electrification	57.9	1.6	2	61.5	0.5	4,293.2	118	154	4565.2	0.3
SC4	Combined Strategies	51.6	2.3	2.1	56	9.4	3,828.0	168	160.8	4156.8	9.2
Rd.: Road Rl.: Rail. Ct.: Coastal											

Currently, trucks with a 94% share of total energy demand from the sector, are the dominant means of freight transportation. According to the numbers shown in Table 4.4, SC4 appears as the most appealing scenario with potential reductions of 9.4% and 9.2%, in energy demand and GHG emissions, respectively. It is worth noting that these reductions are calculated against the end year values associated to the BAU scenario. The BAU case is based on official projections, which predict changes in freight activity, that lead to an overall 0.2 PJ increase. The reduction associated to SC4 was expected as the scenario encapsulates multiple strategies. Although, it can be seen that most of the reduction in energy use (6.1%) is owed to a 5% modal shift to rail. In 2012, railways had a share of 16% of total tkm. By 2019, tkm rail share dropped to 11.5%. Since 2012, there hasn't been major changes in rail infrastructure, so a 5% modal shift is feasible. A higher modal shift to rail could only be justifiable through policies and investments in infrastructure. For instance, accessibility to the railway network could only be enhanced

through a substantial overhaul of railway tracks, enhancing higher train speeds and subsequently more frequent train services. Moreover, the uptake of railways is constrained by the number, locations and resources of intermodal terminals. All these interventions on infrastructure could encourage a significant shift to more efficient means of transportation. In order to appraise for the potential impacts on modal share, it is necessary to carry out rigorous models that can capture and integrate the interaction between economic, geographic and infrastructure attributes. Latter chapters cover the development of a framework (STRATCODE) that takes the challenge and allows to weigh the capacity associated to a fully intermodal system, and the resulting modal share given pertinent changes in network layout and infrastructure. The LEAP model described in this section aids to quantify the impacts, specifically the direct and indirect emissions associated to different transition pathways on freight network topology and infrastructure.

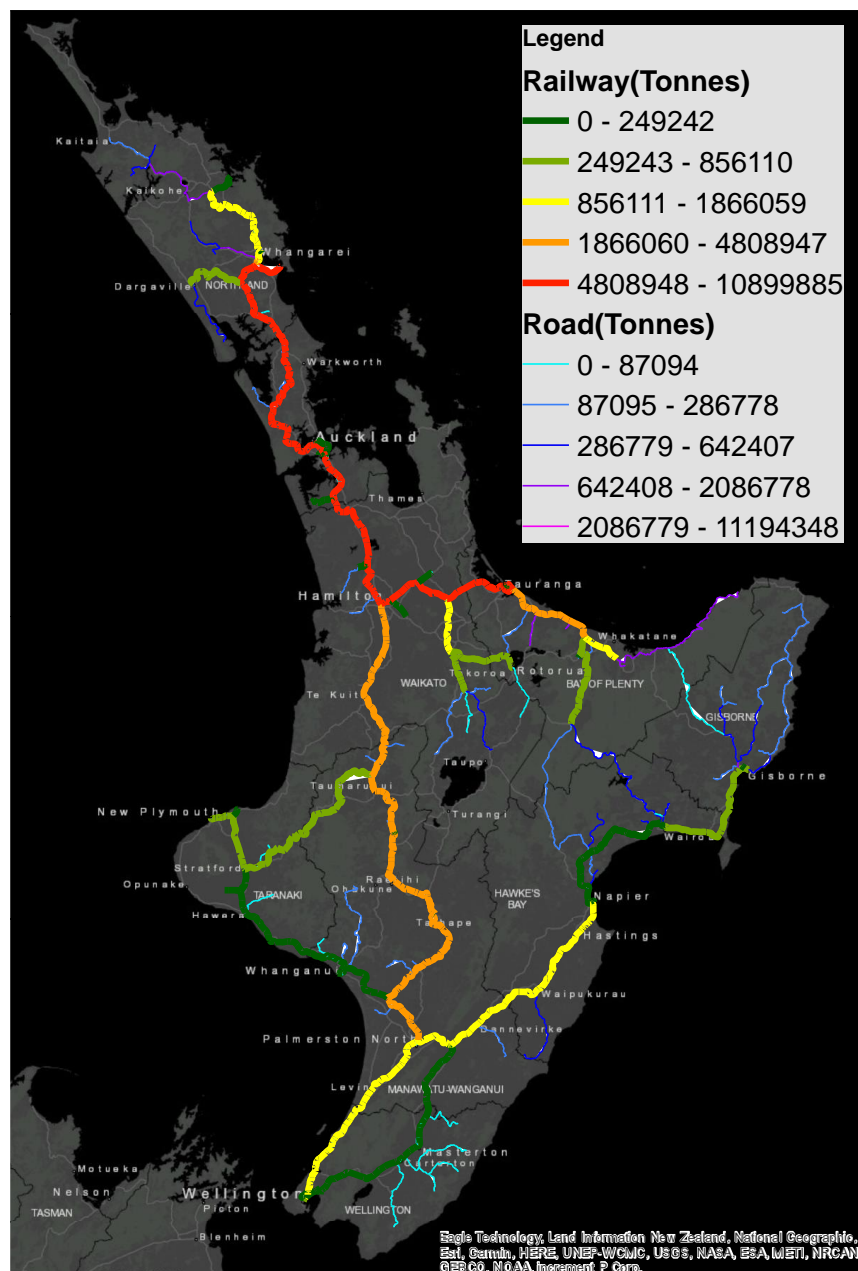
Surprisingly, a drop of 7.1 million tonnes in logging traffic and 0.8 million tonnes of cattle movements resulted in reductions of only 3.7% and 3.6%, in energy demand and GHG emissions, respectively. Forestry production is expected to vary over time, and fluctuations in price and demand on foreign markets can lead to more drastic changes in forestry production. The expected reduction in forestry production is also explained by harvesting strategies in response to aging forests. In regards to winter grazing, the assessment only considered movements from Canterbury, Waikato, Southland and Manawatu-Wanganui regions, so it is fair to say that further reductions in energy demand could be conceivable. Further analyses could consider reductions in imports of vehicles, plastics, and out of season agricultural production.

Despite the considerable traffic through the rail routes between Auckland and Tauranga in the North Island, and Rolleston and Lyttelton in The South Island, the electrification of these

sections does not appear as a promising approach. This observation is mainly explained by the short extension of these routes, that is, despite the magnitude of the volumes transported, energy savings are not substantial as the distances travelled can be as short as 33 kilometers. The effectiveness of rail electrification as a pathway to reduce emissions and oil dependence is highly attached to the nature of the resources used to produce electricity. The potential for electric transport to reduce emissions is often calculated given a constant grid-emission factor, however this process is inadequate because it does not account for how the grid functions once a significant load is added. An important contribution of the model presented under this section is that, the grid emission factor was modelled as a function of resource availability. The electric load for train power consumption was assumed to be constant, as it is expected that the electrified routes will have a high frequency of trains working on a regular basis. This regime of operation makes the electrification of railways more viable than the adoption of a large fleet of personal electric vehicles, as the electric loads can be more predictable and consequently more manageable. The model calculates peak power demand at 6967 MW for the base year. The addition of train electric loads increases peak power to 6996 MW, which does not represent a major change (~0.4%), as the routes involved relies on a short extension of the railway network. In Chapter 8, a network analysis model delivers container import, dairy and log export traffic associated to a fully intermodal system. The network analysis component estimates that, in a best case scenario, a rail modal share of 87% of total tkm is feasible given pertinent changes on network infrastructure. Moreover, the network analysis model estimates that at least 6.7 million tonnes of freight would flow through the railway route comprehended between Hamilton and Northland, as shown in Figure 4.5. Both, a substantial modal shift to rail and the additional electrification of the Northland-Hamilton route would represent an energy reduction of 66% from the current demand at the expense of different interventions on transport and power infrastructure, as the resulting peak power demand would increase from the current 6967



MW to 7767 MW. The calculated peak power demand is a conservative estimate, as a flat load curve was assumed for trains' power demand. The LEAP model developed in this chapter proves to be particularly useful in calculating direct and indirect emissions and in the assessment of the electrification pathway. Hence, the model is also utilized to provide further insights to the assessments carried out in Chapter 6.



**Figure 4.5: Network traffic under a fully intermodal system**

## 4.5. Summary

LEAP software was used as it is becoming the standard toolbox for energy prospecting, it counts with a robust database of emission factors, provides a user friendly logic and environment, and there is a myriad of supporting documents reported in the scientific literature and on the software's website. This chapter presented the development of a LEAP model to quantify energy use and emissions, and also delivered a brief demonstration in the form of a scenario based analysis. Early results from the scenario analysis portray the fundamental role of a modal shift as part of a strategic plan to mitigate GHG emissions in the transport sector. The electrification of railways was also considered and a key feature of the model is its ability to track direct and indirect emissions. This feature is particularly important when assessing the increase in electricity use that may results from a wide national adoption of electric mobility. The transportation branch of the energy system takes transport activity, modal share and energy intensity figures as inputs, which have actually been derived upon the implementation of transport demand models. This feature represents a limitation as there is not a dynamic feedback mechanism between transport demand and energy use. Moreover, more accurate results could be obtained given the availability of load curves for electric trains.

## **Chapter 5: Freight dispersion and mode choice sensitivity to oil prices – A Multiregional Input Output assessment**

Chapter 3 presented statistics on freight activity and energy consumption, denoting a strong nexus between them and exposing the risk of oil dependency. Chapter 4 presented the implementation of a scenario-based approach that focused on the energy transformation side. This chapter addresses the counterpart of the nexus, focusing on the transport demand side through the application of a state of the art transport model based on the Random Utility Based Multiregional Input Output Model (RUBMRIO). RUBMRIO combines traditional spatial input output models with a multinomial logit model for trade and travel choices to represent the distributed nature of commodity flow patterns (Zhao & Kockelman, 2004). Continuing the scenario based narrative from Chapter 4, RUBMRIO is used in this chapter to model the response of mode share and freight flow dispersion to a progressive escalation in fuel prices. An introduction to multiregional freight transport models was presented in Chapter 2, and in this chapter the RUBMRIO algorithm is implemented and validated. The methodology is applied to New Zealand, using local geographical data and technical coefficients. The methodology also covers the estimation of coefficients for the model's embedded logistic function. In the final step, commodity specific energy intensities are used to translate transportation flows into figures of energy consumption and results are reported for scenarios based on different fuel prices.

In alignment with the thesis objectives, the methods and results addressed in this chapter open a space for discussion on the scope and limitations of current freight transport models. The model relies on a vast amount of data, and often, as it was the case in this chapter, the modeler has to make several assumptions. According to the results, a pronounced increase in fuel prices leads to a substantial shift to rail. However, it is shown that the Keynesian footprint on the

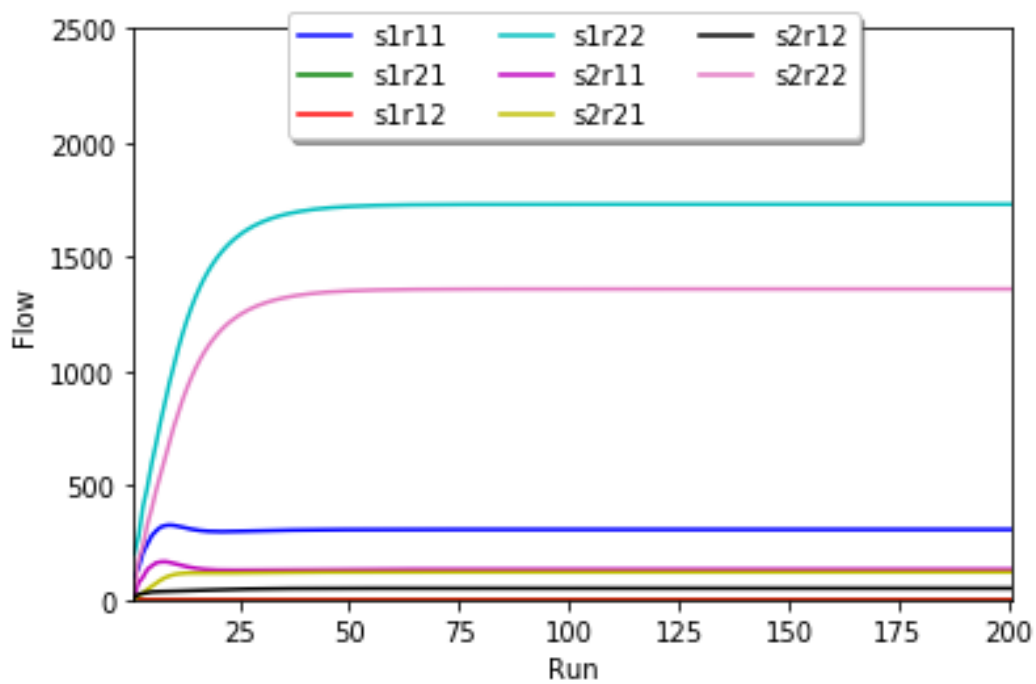
model may lead to unreasonable results, as after a fuel price threshold, remote origins are preferred over local sources. This behavior or feature may represent a major limitation especially if the model is used as a tool for the formulation of long term strategies and policies on energy and transportation systems. Moreover, the preference for remote sources does not necessarily align with carbon mitigation pathways that foster responsible localized consumption.

## 5.1. Model Validation

The algorithm was coded in Python and executed using a numerical example, please refer to the script included in Appendix A. The model was validated by means of comparison against the convergence analysis presented in Zhao and Kockelman (2004), which uses the same numerical values. The example is based on the interaction between two regions, for commodities from two sectors. Dispersion parameters are set to  $\lambda_1 = 15$  and  $\lambda_2 = 0.2$ . The values used for model validation are given in Table 5.1. For this case, the utility function only considers one transportation mode and it is assumed that technical coefficients are the same for all regions. **Figure 5.1** presents the estimates for multiregional flows after each iteration. The legend makes a distinction amongst different sectors, for instance, s1r12 corresponds to the flow between regions 1 and 2, for commodities from sector 1. It can be seen that all flows converge to the same values reported in Zhao and Kockelman (2004), which confirms the model's validity. The model's behavior is expected as the greater flows from the sector with the highest  $\lambda$  are intraregional, and interregional movements are significant for the sector with the lowest  $\lambda$ .

**Table 5.1:** Values for numerical example

Transportation Costs (\$)		Technical coefficients		Final Demand	
$d_{11}$	2	$a_{1,2}^{11}$	0.2	$Y_1^1$	100
$d_{12}$	10	$a_{1,2}^{12}$	0.8	$Y_2^1$	200
$d_{21}$	10	$a_{1,2}^{21}$	0.7	$Y_1^2$	20
$d_{22}$	1	$a_{1,2}^{22}$	0.1	$Y_2^2$	50

**Figure 5.1:** Convergence of multiregional flows

## 5.2. Methodology

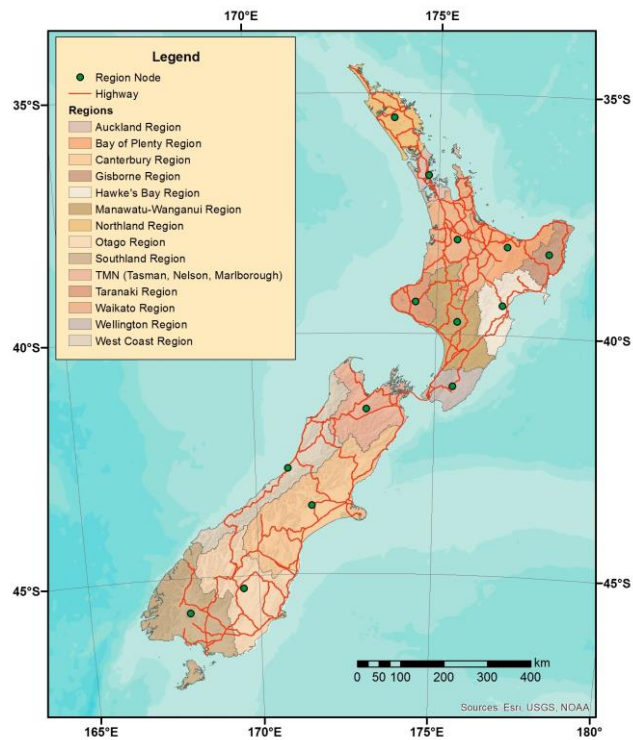
The model studied in this chapter requires a substantial amount of data, which is actually a major limitation that was tackled at the expense of several assumptions. This section describes

the generation of geographic and economic data. It also provides details behind the estimation of coefficients for the origin/mode nested logit model.

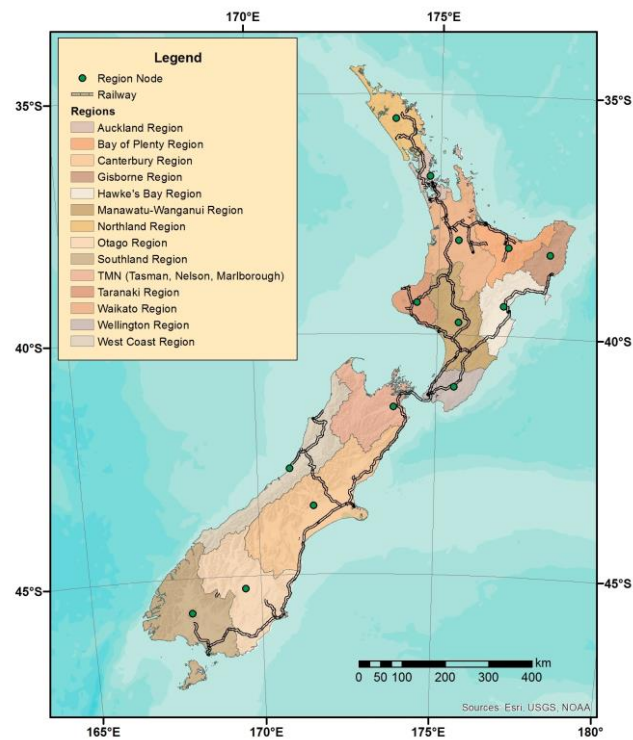
### ***5.2.1. Geographic Data***

Origin – Destination cost matrices were created using the shortest route road distance between each node as the cost parameter. The nodes represented each one of the fourteen regions considered on the present case study, and its location corresponds to the region centroid. Intraregional distances were assumed to be equal to the radii of a circle with an area equivalent to the actual region. The geographic information datasets for highway and railway layers were obtained from the *koordinates1* web site (*koordinates*, 2015a, 2015b). The regions demarcation layer was obtained from the Stats NZ website (Stats N. Z., 2013) (Stats NZ, 2013). The acquisition of the matrices was made with the “OD Cost Matrix” tool from ArcGIS Network Analyst extension. Networks for the aforementioned cases were created, with a prior process of topology inspection and correction for the arcs datasets. Figure 5.2 shows the representation for regional boundaries and transportation networks.

The GIS environment presented in this and subsequent chapters managed feature datasets based interchangeably on the WGS84 geographic coordinate system and on the NZGD 2000 New Zealand Transverse Mercator projection. The reason for choosing WGS84 coordinate system is its adoption by standard platforms like GPS and Google APIs.



*New Zealand Road Network*



*New Zealand Railway Network*

**Figure 5.2:** Representation of New Zealand Regions along with Road and Railway Networks

### ***5.2.2. Technical Coefficients***

Lang (2016) proposed a methodology to assess fuels shortages through explicit modifications of the coefficients of input output models and through a monetary constraint analysis that was based on fuel price fluctuations; the methodology contemplated the application of the RAS technique to update the national input output table for New Zealand. Once the updated table was obtained, it was further used to generate regional input output tables through a non-survey method known as Location Quotients (LQ). A LQ refers to the proportion of a region's output that is contributed by a specific sector; the practicality of the method resides on the possibility to employ economic activity indicators such as employment, instead of total output (Miller & Blair, 2009).

Sixteen regional tables generated from Lang's work were inputs to the model described in this chapter. New Zealand's productive means were aggregated into fifty one sectors. Further aggregation was required given that the other source of information for this model is based on the National Freight Demand Study (NFDS) for New Zealand, so that, the economy ended up being aggregated into twenty three sectors. The final demand from every sector in every region was also obtained from these tables, it was estimated to be the sum of public and private consumption and total exports.

### ***5.2.3. Parameter estimation for Nested Logit Model***

The RUBMRIO formulation addressed in this chapter considers modelling freight flows, where the choices or decisions made are defined by both the origin of the flow and the mode used to reach a particular destination. Buyer's decisions or choices follow a random cost minimization,



so they will tend to obtain inputs from the regions that offer the cheapest prices. Equation 3-10 shows that prices depend on transportation costs, which in this case are based on distance. Dispersion parameters ( $\lambda_n$ 's) reflect how some commodities are more sensible to distance than others. Mode choice parameters ( $\beta$ 's) are associated to the lower level of the nest and they are specific to transportation modes (rail and road) and to commodities as well. Coastal shipping was not considered since it has a very small share nationwide, approximately 2% (Deloitte, Richard Paling Consulting, Murray King, Francis Small Consulting, & Cooper Associates, 2014).

The nested logit model is appropriate in this particular model, since it is based on the assumption that some choices share common attributes in their random terms, so that, the random term of nested choices can be decomposed into a portion specific to each alternative and a portion associated to a specific set of alternatives (Koppelman & Bhat, 2006). The datasets used to estimate origin and mode choices for freight flows were also derived from the NFDS. The NFDS provides trade flows between regions for each type of commodity. The study also contemplates fourteen regions for New Zealand. The Tasman, Nelson and Marlborough regions are aggregated into one (TMN) (Deloitte *et al.*, 2014).

In the lower level of the nested model, mode choices were estimated for each sector. The explanatory variables are the network distances associated to each mode. Unfortunately, the NFDS only provides mode choice observations for total freight movements, so mode choice parameters that were estimated upon these observations were assumed to apply for all commodity types. The conditional probability of choosing mode  $n$ , for a given  $ij$  pair is given by:

$$P_{t|ij}^m = \frac{\exp(V_{ij,t}^m)}{\sum_s \exp(V_{ij,s}^m)} \quad (3-12)$$

Where the systematic utility  $V_{ij,t}^m$  is:

$$V_{ij,t}^m = \beta_{0,t} + \beta_t d_{ij,t} \quad (3-13)$$

The Alternative Specific Constant (ASC) for road ( $\beta_0$ ) was set to zero, in order to permit statistical identification of other parameters. The parameters for mode choice were estimated using *larch*, which is an open source python library for estimation of logit-based discrete choice models. The estimates and statistics obtained for mode choice are shown in Table 5.2.

**Table 5.2:** Mode Choice Multinomial Logit Model Parameter Estimates and estimation statistics

Parameter	Value	Standard Error	t-statistic
$\beta_{0,rail}$	-3.32	0.154	-21.5
$\beta_{rail}$	0.000957	0.00156	0.613
$\beta_{truck}$	-0.00102	0.00162	-0.634
No. of observations	1388		
Rho-squared w.r.t null parameters	0.719		

The upper level refers to the choice probability that buyers will acquire inputs from origin  $i$ .

Choice probability is given by the following expression:

$$P_{ij}^m = \frac{\exp(V_{ij}^m)}{\sum_k \exp(V_{kj}^m)} \quad (5-1)$$

The systematic utility  $V_{ij}^m$  refers to the expression previously defined in Equation (3-9). For the two level model described, the parameters were estimated using the sequential procedure proposed in M. Ben-Akiva and Lerman (1993). The idea behind this technique is that parameters from the lower nest are estimated first. Then, given the coefficients estimated in the previous step (lower level choice) and the interregional distances associated to each mode, the *logsum* term from Equation (3-9) is calculated for each *ij* pair,. The *logsum*'s are considered as costs for the estimation of the dispersion parameters ( $\lambda_n$ ). The estimates and statistics obtained for origin choice are shown in Table 5.3.

**Table 5.3:** Origin Choice Multinomial Logit Model Dispersion Parameter Estimates and estimation statistics (1390 observations for each sector)

<b>Sector</b>	<b><math>\lambda_n</math></b>	<b>(R-square)</b>
Milk	13.80	0.7304
Dairy products	6.28	0.3955
Timber	10.00	0.5952
Wood and paper	2.47	0.1012
Livestock	6.63	0.4211
Meat	14.74	0.7387
Horticulture	11.66	0.6474
Other agriculture (grain)	4.25	0.2459
Wool	2.14	0.0856
Fish	15.94	0.7866
Coal	6.12	0.4640
Petroleum	3.06	0.1474
Aggregate	11.40	0.6486
Limestone, cement and concrete	9.99	0.5941
Steel and aluminum	4.62	0.2688
Manufactured goods	2.96	0.1394
Supermarket	3.54	0.1862
Post, courier	1.34	0.0321
Imported cars	4.76	0.2504
Other minerals	4.40	0.2604
Waste	29.67	0.9338
Services	9.04	0.5527

#### ***5.2.4. Energy intensity for every sector and mode***

The first step is to actually convert monetary flows to tonnes. For each sector, total monetary flows estimated through the execution of the RUBMRIO model were divided by the total tonne flows that were reported in the NFDS. Twenty one sector specific factors were obtained. The sector service was no longer considered for further calculations as they do not represent physical flows within the territory. These factors were applied over each matrix of monetary flows. In total, there were forty two matrices, each one of them being sector and mode specific. A second conversion procedure contemplates the translation of tonnes into units of energy consumption. The factors utilized for the calculations are also sector specific. Andrés and Padilla (2015) analyzed the determinant factors behind energy intensity of road freight transport. It was assumed that the intensity values provided by Andrés and Padilla (2015) match the intensities of the road transportation sector in New Zealand. Intensities for rail transportation were derived from energy intensities reported in the LIPASTO database for diesel driven mixed freight trains (LIPASTO, 2017b). The energy intensity values employed in the calculations are specified in Table 5.4.

**Table 5.4:** Energy Intensity by sector and by mode

Sector	Road	Rail
	(MJ/tkm)	(MJ/tkm)
Milk	0.580	0.340
Dairy products	1.000	0.586
Timber	0.990	0.580
Wood and paper	0.740	0.434
Livestock	1.470	0.862
Meat	1.000	0.586
Horticulture	0.880	0.516
Agriculture (grain)	0.720	0.422
Wool	1.310	0.768
Fish	1.000	0.586
Coal	0.740	0.434
Petroleum	1.200	0.703
Aggregate	0.650	0.381
Limestone and cement	0.930	0.545
Steel and aluminum	1.350	0.791
Manufactured goods	1.250	0.733
Supermarket	1.250	0.733
Post and courier	1.250	0.733
Imported cars	1.350	0.791
Other minerals	0.650	0.381
Waste	0.650	0.381

### 5.3.Results and discussion

The main goal was to study the impact of transportation costs on the overall dispersion of the freight flow pattern and on mode share. It has been estimated that in average fuel costs represent up to 21% of the total costs for road transportation and 14% for rail transportation (Bureau of Transportation, 2016). These proportions were incorporated to the calculations. For instance, a 100% increase in oil prices will be reflected in a 7% and 11% increase in rail and road transportation costs, respectively. These values were applied as factors to the transportation cost matrices for each mode. The RUBMRIO model was executed and it delivered a new flow pattern that corresponds to the updated transportation costs. This process was carried out for a Business As Usual (BAU) scenario that represented the system with the current oil prices. The process was also performed for four alternative scenarios where oil prices were doubled, tripled, quadrupled and quintupled. The OD flow matrix for the BAU scenario matches the configuration that is reported in the NFDS, where flows are not dispersed (located on the matrix diagonal) and there is not a sign of major trade between islands. According to the results, modal shares are 6.3% and 93.7%, for rail and road respectively. This distribution is very similar to the modal share reported in the NFDS (7% rail, 91% road), which suggests that the origin and mode coefficients that were estimated in this study, closely reflect the behaviour of freight operators in New Zealand.

Richard Paling Consulting (2009) conducted a survey with industry participants to explore what were the main determinants for freight mode choice in New Zealand. From most to less important, with 5 being the highest possible score, the ranking obtained was: reliability (4.75), product care (4.64), safety (4.58), timeliness (4.31) and cost (4.23) (Richard Paling Consulting, 2009). An ASC was considered and according to the estimations, this coefficient is statistically significant ( $p < 0.01$ ). It seems that the ASC ( $\beta_{0,rail}$ ) appropriately allows for statistical

identification of mode choice preference criteria not considered in the model. Furthermore, the mode coefficient estimated for rail is positive and small, suggesting a higher preference for this mode over longer trips.

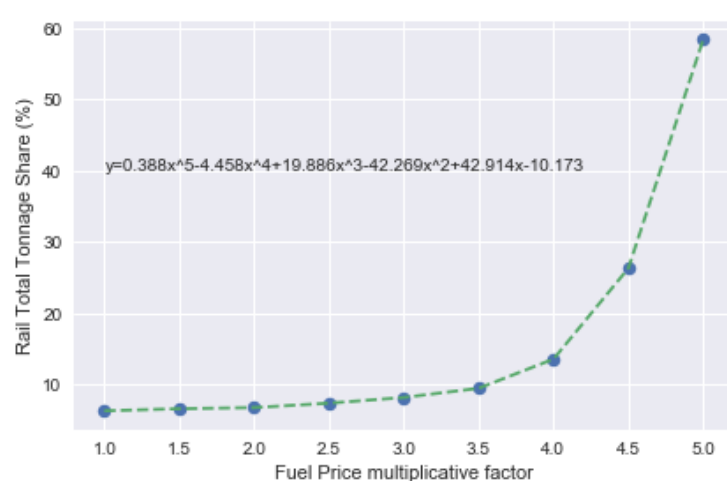
Data availability is a major limitation for the development of MRIO models. Ideally, the model requires a social accounting matrix for every region that is considered in the analysis. In this case, regional technical coefficients were previously estimated upon a national accounting matrix and regional statistics. Additionally, mode and origin choice parameters were calculated upon the execution of a logistic regression package over a dataset that corresponded to the observations reported in the NFDS. Consequently, the analysis was based on observations made for the entire freight sector, that is, the study did not present sector specific observations for mode choice. Furthermore, sectors such as livestock and waste, operate entirely through road transportation. Given these circumstances, these sectors were included assuming that they are based on the same coefficients as the remaining sectors. Each sector will most likely be characterized by its own set of coefficients, given that their physical characteristics appeal for choice determinants that may have more weight or importance than transportation cost. The assumption that all sectors follow the same estimated mode coefficients certainly reduces the reliability of the model in terms of predicting travel demand. Nevertheless, the main goal of the approach was not to provide a precise estimation of travel demand, but rather, understand the impact of transportation costs on the overall freight dispersion and the importance of relying on a strategic network that allows for modal shift given a critical and highly possible scenario.

The omission of coastal shipping as an alternative mode is also a feature that may underestimate the overall reliance of the New Zealand freight transportation network. Data availability is a recurring limitation that forced us to incur in the two mode formulation. According to the NFDS, the current modal share for coastal shipping is approximately 2% and it is almost

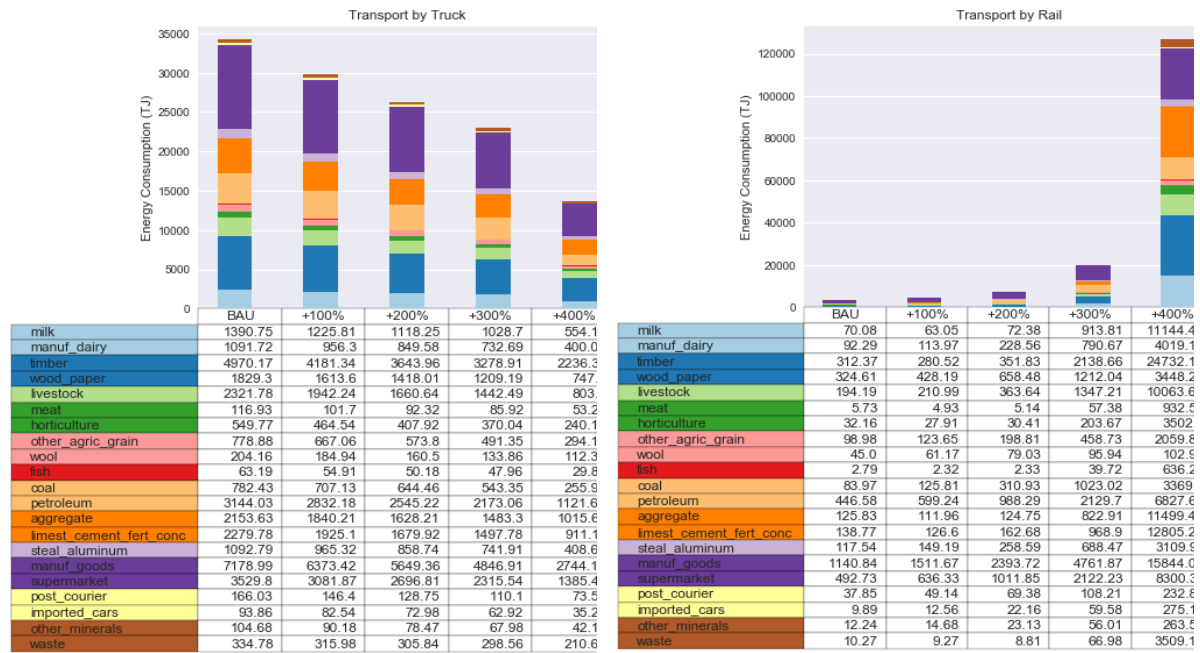


entirely exclusive to petroleum shipments. Hence it was infeasible to provide proper coefficients that will reflect sector specific preferences for this mode. The presented methodology considers that transportation costs are proportional to travelled distances, however, freight logistics are far more complex than that.

It can be evidenced from **Figure 5.3**, that as prices increase, rail starts becoming a more attractive option. Rail's tonnage modal share (58%) supersedes that of truck transport (42%) in the last scenario (400% fuel price increase). Given an extreme high price for oil, the Canterbury region starts becoming an important center of trade between islands.



**Figure 5.3:** Rail Tonnage Share as a function of fuel price multiplicative factor



**Figure 5.4:** Freight Transportation Energy consumption for different fuel price scenarios

The last step of the analysis refers to energy consumption calculations. It can be seen from Figure 5.4 that commodities from the retail sectors are mainly shipped by road. This behaviour may follow the preference for modes that are flexible enough to respond to just on time deliveries while preserving product care features during transportation. It can be deduced that when fuel prices exceed the 300% increase threshold, rail starts becoming the driving force behind trade. Even though, rail is a more energy efficient mode of transportation than trucks, the energy consumed by the entire transportation systems rises abruptly after the aforementioned threshold. This peculiarity can be explained by the ability that railways have to develop economies of scale. In this particular case, the Canterbury region becomes a major centre for inter-island trade. Given the case that the national rail infrastructure connects the entire country, the differences for input prices between regions start dropping and it starts becoming more economically feasible to purchase products from other regions.

## 5.4. Summary

A recent report by the International Monetary Fund (IMF) suggests that the current era of prolonged low oil prices is likely to be followed by a period where oil prices may abruptly overshoot their long term upward trend (Arezki et al., 2017). This statement is based on the idea that recent low oil prices have caused a decline in investments for oil exploration and extraction technologies. Subsequently, this behaviour contributes to a reduction in oil supply that can lead to an accelerated escalation of prices. The results in this chapter suggest that beyond the 300% fuel price increase threshold, the national freight system will become vulnerable if there is not an adequate railway system to support economic trade within the region. Not so long ago, we experienced a drastic escalation of oil prices. In June of 2003, the price of an oil barrel was approximately 40.49 USD, and five years later the oil barrel reached a record price of 157.73 USD (Macrotrends, 2017).

Multiregional Input Output Models have been used in the past to estimate transport demand and assess the impact of new transportation infrastructure. The method presented in this chapter was not focused on the precise estimation of travel demand, but rather on understanding how vulnerable the current system is, taking into account that the freight transportation system is highly dependent on road transport and on the fossil fuels that are consumed by this mode. It is worth noting that, as it is the case with any other model, it is complex to incorporate all the dynamic feedbacks that occur in reality. For instance, it would be important to analyze the impact that a drastic mode shift will have on the configuration of the entire economy. The model relies on the assumption that technical coefficients remain constant during the period of analysis. However, a drastic mode shift to rail, will definitely imply that less resources will be assigned to the construction and maintenance of new roads. Furthermore, less resources will be assigned to import new vehicles from overseas. Under these circumstances, it may be

appropriate to consider complementary methods to incorporate essentiality metrics over the products that are being transferred within and outside the country.

According to the calculations, beyond the 300% price increase, energy use skyrockets for the entire freight transport system. Decisions are driven by a logistic function that assigns higher probabilities to the choices that deliver the least transportation costs. This cost minimizing approach leads to a substantial shift to rail. However, the relatively low cost of rail also provokes undesired consequences, as remote locations for production sources are prioritized over localized consumption. Apparently, the model has the capability to mimic what is known as the rebound effect. In other words, the introduction of energy efficient technologies leads to an overall energy demand that offsets the potential energy savings. This is a particular issue that illustrates the inadequacy of input output assessment in the context of long term decision making. Furthermore, the risk of a rebound effect strengthens the idea to include metrics for essentiality in the analysis. Besides realizing the finite nature of fossil fuels, we need to acknowledge that our economy is subject to physical and biological laws and the assumption of unconstrained mobility is pushing our planet's resources to the limit.

The model presented in this chapter aimed to address the gap between transportation demand and energy accounting methodologies, but the findings suggest that it may not be a reasonable approach for long term assessment, as the factors of production within regional economies remain fixed. Moreover, the embedded logistic function drives decisions in a cost minimizing manner, leading to unreasonable consumption patterns that do not necessarily align with adaptation strategies that embrace localized consumption. In context, the analysis focuses on the effect that fuel prices have on transportation costs and subsequently on the overall dispersion of the freight flow pattern. The RUBMRIO model is applied and the findings make the case for the inadequacy of the method for long term transportation planning.

Modal share for coastal shipment in New Zealand is approximately 4% (Richard Paling Consulting et al., 2019), meaning that there were not enough trip observations for the adequate estimation of mode and origin choice coefficients. The omission of coastal shipment is a big limitation of the analysis, and it is likely that it will be an essential alternative, particularly for interisland transportation in a fossil fuel constrained future.

## **Chapter 6: Framework for strategic concept design of freight systems**

The overall aim of the research is to advance freight supply chain analysis to inform low carbon transition pathways. Earlier chapters provided a background for characterizing the freight system historical development and current demand. The scenario-based narrative has included the implementation of the energy planning (Chapter 4) and input output (Chapter 5) models, allowing to build understanding on the relationships between transport activity, energy demand, technological and economic interventions. Chapter 6 introduces a framework for STRATegic COnccept DESign of Freight Systems (STRATCODE). The framework provides a detailed picture of the multimodal interactions within a future freight system concept as a strategic pathway to cut GHG emissions to meet climate change mitigation goals. STRATCODE combines three components: freight distribution, network analysis and GIS-based Discrete Event Simulation (DES). The consideration of different components enhances the realization of different objectives. The freight distribution model is conceived as a preliminary component and allows to disaggregate interregional flow matrices into facility-to-facility OD pairs. The distribution component overcomes data availability limitations and also fulfills the purpose of data formatting. The combination of network analysis and discrete event simulation allows to further disaggregate OD pairs, enhancing the logistic component through the identification and implementation of intermodal hubs or transfer nodes. Traffic assignment, mode allocation, network planning, hub location, train scheduling and terminal design problems have already been covered in the literature, but the novelty of the proposed approach stands in considering them together as part of a strategic planning framework to assist the generation of a future concept for the freight system in the transition to a low carbon system.

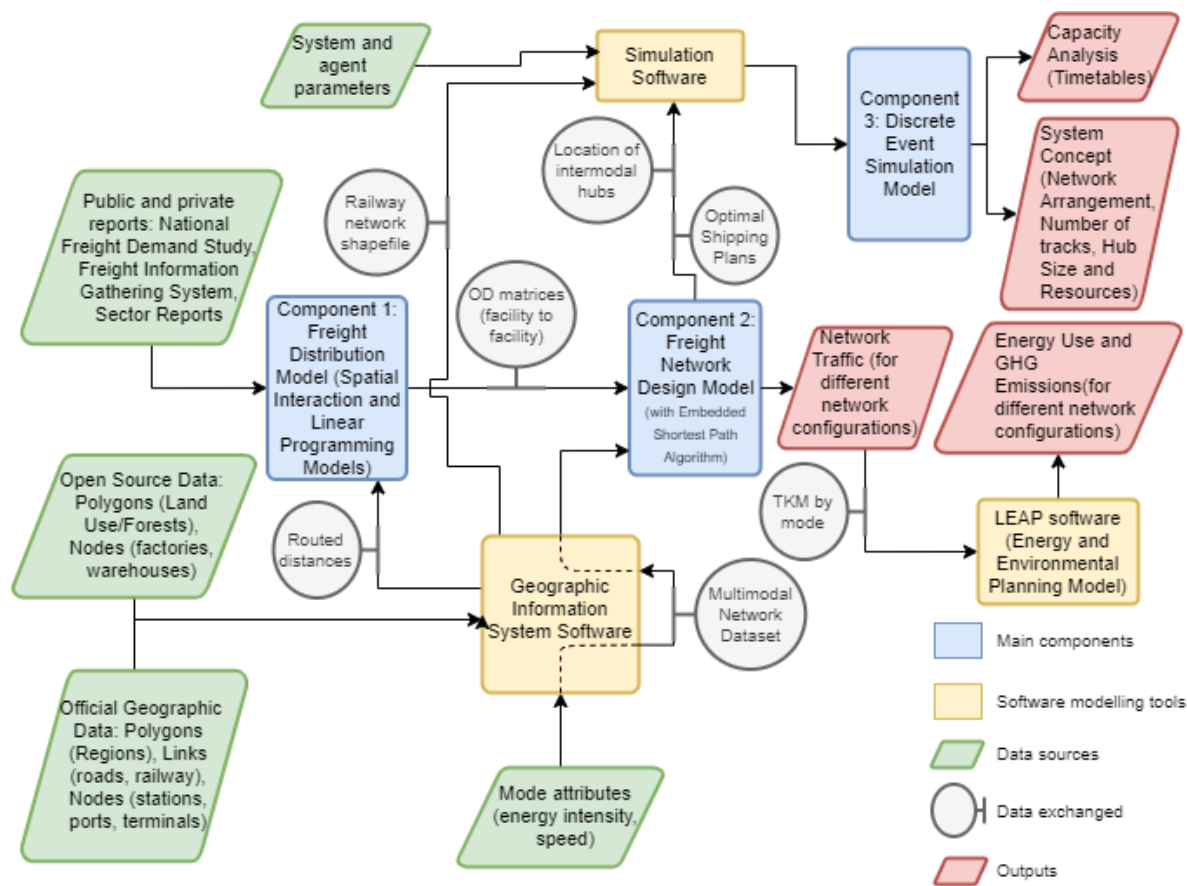
The North Island of New Zealand is used as a case of study. STRATCODE is implemented to study the impact on energy use and freight demand of different freight infrastructure

interventions. The low carbon system concept has the freight railway as a backbone structure. The remaining chapters of this thesis cover specific details on each component and describe the process behind the generation of a future concept of the system.

The consensus amongst experts and authorities is the need for a long-term vision, not only for transportation, but also for all sorts of complex systems (Bakker, Zuidgeest, De Coninck, & Huizenga, 2014; Pietzcker et al., 2014). A new method has been proposed to break the path from historical trends and build future concepts that meet the essential requirements of an activity system while operating under biophysical constraints (S. Krumdieck, 2019). The task of developing a path-breaking future concept is challenging because there is limited experience on the long-term design of complex engineered systems like transportation. The purpose of a path-break concept for freight transport systems is to facilitate engineers and planners to communicate with policy makers the configuration, capacity and resources needed by a system in order to meet the essential freight duty while achieving fossil fuel reduction targets. The proposed framework requires compliance with engineering science, resource availability and engineering feasibility (S. Krumdieck, 2019).

## **6.1. Framework for Strategic Concept Design of Freight Systems (STRATCODE)**

Figure 6.1 shows a schematic of the interconnection between the three main components of STRATCODE: freight distribution, multimodal network analysis and agent based discrete event simulation. Figure 6.1 also shows the data sources, the utilization of auxiliary software tools, data flows and modelling outputs.



**Figure 6.1:** Scheme for concept generation framework

### 6.1.1. Data Sources

There are several data sources feeding models within the distribution component and also used as inputs to be processed through the GIS and simulation auxiliary software tools. Multiregional OD matrices for different commodities extracted from the NFDS, export and import volumes for different ports extracted from the FIGS, and statistics from sectoral reports are employed for the execution of the freight distribution component, more details are provided in Chapter 7. The following types of geographic datasets are used and processed through ArcGIS:



- Point features: Locations of factories, ports, warehouses and railway stations.
- Polygon features: Land use dataset for exotic forests.
- Line Features: Edges from the road and railway network.

The framework contemplates the utilization of a multimodal network dataset. There is a set of attributes (distance, time and energy use) for every edge of the network. Distance attributes are delivered through the software's network analysis toolbox. The two remaining attributes are functions of distance attributes and auxiliary mode (road and rail) and operation (transport and transshipment) specific values for energy intensity and speed, more details are provided in Chapter 8.

The simulation component comprehends the interaction of different agents and resources. Before the execution of the simulation model, users are allowed to setup the values of parameters associated to these agents, including number of wagons per train, and train and truck cruise speeds. In regards to resources, users are allowed to specify the quantity of cranes/forklifts at each port, and the corresponding transshipment times. Loading/unloading times were based on figures reported in the literature and on timed observations. Elements from the network layout are also adjustable, specifically the use of single or double tracking for different segments of the railway network, more details are provided in Chapter 9.

### ***6.1.2. Components***

The first component, freight distribution, makes use of various transport distribution modelling approaches. It uses data from the latest NFDS, the Freight Information Gathering System (FIGS) and open source geographic data. Several firm-to-firm OD tables are generated upon

the execution of the distribution model, which are subsequently used as data inputs by the sequential optimization-simulation approach that encompasses the network analysis and discrete event simulation components. Scripts for the distribution and network analysis components are coded in Python language and make use of ArcGIS software functionality, especially from the Network Analyst and Spatial Analyst extensions.

The second component, a multimodal network dataset, is built upon line features representing roads, railways, and transshipment links. Mode-specific attributes are also used during the construction of the network dataset. Network Analyst's OD Cost Matrix function is applied to obtain routed distances needed for the execution of the spatial interaction and linear programming models embedded in the freight distribution component. The network dataset is also used as a data input for the freight network design component, which runs a shortest path routine (Dijkstra's algorithm) for every OD pair, using either time or energy use attributes on each execution.

The third component is a GIS-based discrete event simulation model that enhances the analytical solution provided from the optimization component. Scripts for the simulation component are coded in java and make use of Anylogic software functionality. During the simulation, agents within a GIS space interact amongst each other in response to shipping orders generated as discrete events. Shipping plans are based on optimal paths queried from a database. The simulation accounts for truck and train trips and loading and unloading operations. The architecture of the simulation model allows for exploration of different experimental setups defined by the availability of resources, network configuration and agent attributes. On each simulation experiment several parameters are tuned up, including train speed, number of forklifts, number of cranes, number of wagons per train, and segments with double tracking.

### **6.1.3. *Modelling Outputs***

The first output from the network analysis component is a traffic assessment through the network, with detailed volumes of different commodities assigned to every edge. These volumes include traffic through intermodal nodes. The volumes (tonnes) and distance (kilometres) assigned to every edge are used in the estimation of transport activity (tonne-kilometre) which are translated into figures of energy use and GHG emissions through the execution of the energy and environmental planning model described in Chapter 4. Network traffic is also used to filter out a set of hub candidates with significant flows. The selected hubs are modeled as agents during the simulation step. The second output is a database that contains records of shipping plans (pick-up, transfer and drop-off locations) for every shipment, and provides the connection between the network analysis and simulation components.

The simulation component allows to carry different simulation experiments, each with a characteristic arrangement of parameters. For every experiment, performance is measured in terms of size and utilization of railyard tracks, number of resources employed at each terminal, utilization factors, train timetables, and queue size at ports. Furthermore, after the identification of a setup that meets the user's requirements, the information can be processed in order to quantify the costs associated to a specific setup.

## **6.2. Summary**

The framework presented in this chapter fits within the new generation of transport models that embrace a multi-layered conceptualization of the freight system that includes underlying supply chain dynamics. Several of these recent modelling approaches still adopt discrete choice

formulations for mode and route assignment, which may be practical and effective for short to midterm planning decisions but may not be rational for long-term strategic planning. STRATCODE takes a different approach and embraces a deterministic component that aims to deliver a conceptual design that fosters the use of alternative and more efficient modes of transportation. Moreover, STRATCODE provides a bridge that connects macro and micro distribution structures, enhances the assessment of logistic operations, and identifies interventions that can improve the performance of different supply chains while fulfilling a long term commitment to reduce fossil fuel dependency.

Chapter 7 presents the development of a freight distribution model, including the methodology implemented and the corresponding results in the form of geographically represented OD pairs. The network model allows to generate optimal shipping plans for several commodity-specific OD pairs, delivery routes, allocate transport modes to every leg of the transport chains, quantify traffic through the network, and select intermodal hubs. Chapter 8 covers in more detail the development of the second component, including the methodology behind the construction and implementation of the model, and the corresponding results. Simulation allows to evaluate different infrastructure arrangements in order to deliver satisfactory system performance in terms of shipping time, resource utilization, train frequency and queuing time at terminals. Chapter 9 focuses on the third component, including model development, implementation and results.

The combination of components two and three addresses the problem of strategic planning from different points of view. From the perspectives of transport planners and drayage operators, STRATCODE allows to deliver routes, scale traffic and identify intermodal hubs associated to optimal scenarios. For network and terminal operators, STRATCODE analyses railyard setups, rolling stock and handling resources, needed to enhance the analytical solution

from the network assessment. Specific details on the structure, logic and performance indicators related to each component are provided in the next chapters, using New Zealand as a case of study.

The combined framework presented in this chapter embraces the feature of a connecting central database. The approach also inherits some components from the agent-based freight models presented in Chapter 2. It aims to study the role of strategically located hubs as agents of consolidation. It integrates structural and control elements used on previous studies. In regard to structural elements, the approach conceives the interaction of agents involved in the production and transportation of products. As for control elements, the model enhances managing information associated to shipping orders and coordinating transport routing and resource utilization in terminals. The framework focuses on a long-term vision that fully embraces multimodality as a strategic pathway to support national commitments towards climate change mitigation. Accordingly, the network component delivers a deterministic solution. The simulation counterpart is used to gauge the system configuration and capacity required to meet the freight task associated to a scenario resembling a radical transformation that can potentially lead to a substantial reduction in energy use and emissions.

## **Chapter 7: Component 1 - Freight Distribution Model**

Freight transport models rely on accessibility to micro-data, which is often scarce as commodity flow surveys are costly and infrequent (M. E. Ben-Akiva et al., 2016). Moreover, data on individual shipments are usually proprietary and firms are often reluctant to disclose this information to clients, competitors and the public (Lóránt Tavasszy & de Jong, 2014). A new approach is needed to obtain high resolution freight data for better safety and efficient management of supply chain capacity. This chapter reports the development of the first component of STRATCODE, a preliminary freight distribution model that combines iterative proportional fitting, spatial interaction modeling and linear optimization to transform regional production-consumption tables into facility-to-facility matrices. The first component disaggregates interregional production-consumption matrices into facility-to-facility matrices. The distribution component is applied to derive matrices for log exports, dairy exports and containerized imports. These sectors were considered as the products involved represent at least 50 percent of the total freight movements in New Zealand. Component 1 relates transportation flows to representative origin and destination entities within the network, upon a novel arrangement of geo-processing and web scrapping scripts. Furthermore, the execution of Component 1 also serves as a preliminary step within the STRATCODE framework, as it allows to setup the data structures needed as input for the forthcoming optimization and simulation components.

The methods presented in this chapter adapt to the characteristic features of the sectors involved and to data availability. Section 7.1 covers the distribution of flows for log exports, where a linear optimization model is formulated upon interregional matrices obtained from the NFDS. Section 7.1 also covers the identification of representative forest locations, upon the use of a land cover dataset and the application of several geo-processing functions. Sections 7.2 and 7.3

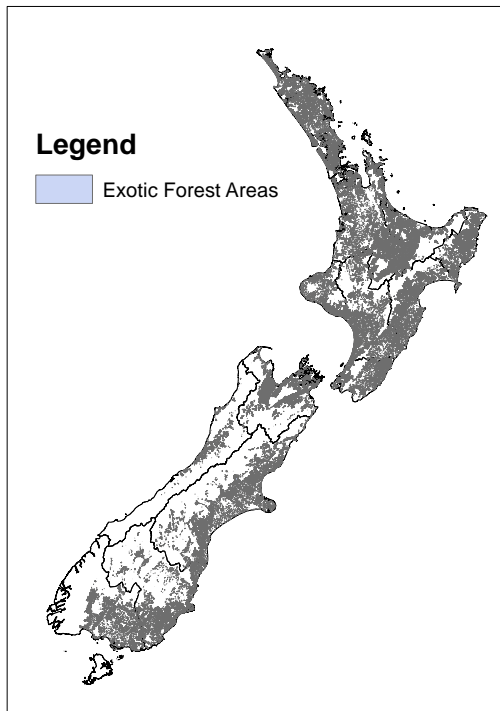
address the distribution of flows for dairy exports and container imports, respectively. The method integrates iterative proportional fitting procedure (IPFP), calibration of gravity model, and linear optimization. Regional milk production and population are used in the calibration of gravity models for flows of dairy exports and container imports, respectively. In Section 7.4 the results in the form of firm-to-firm matrices are geographically represented and discussed.

## **7.1. Distribution method for log exports**

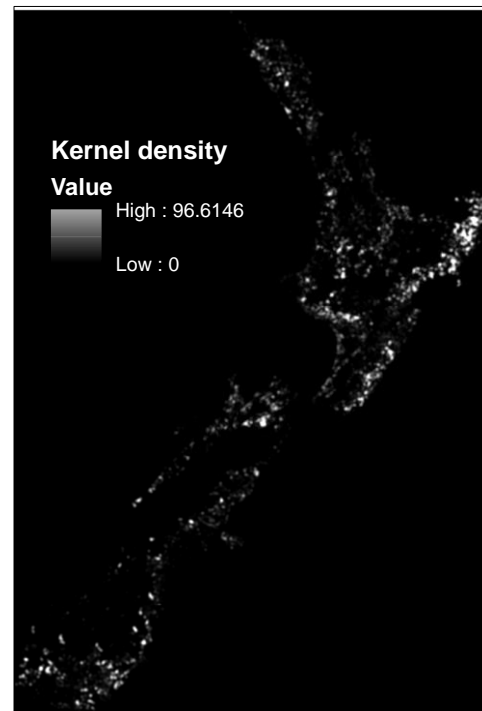
Tables from the NFDS report multiregional movements of commodities between two types of facilities. This is the case for the transportation of logs from forests to ports (Log Exports) (Deloitte, Richard Paling Consulting, Murray King & Francis Small Consulting, et al., 2014). In this section, Log Exports tables are used in the formulation of a Linear Programming (LP) problem. Logs are mostly harvested from exotic forests and transported to ports, sawmills, panel factories and pulp factories. The accurate geographic representation of forest entities is an essential departing step. The New Zealand Land Cover Database (LCDB) is a file with geographic data that is available to the public through the Land Resource Information Systems (LRIS) Portal (LRIS, 2015). The file contains 497,833 GIS features, from 33 thematic classifications for New Zealand's land cover, 20% of which is exotic forest. Given the wide spread of forests, representative locations were derived using the original LCDB file. The procedure allowed for the identification of zones with a high density of forest areas, which became the input of a sampling procedure that led to the obtainment of 75 forest points. This involved the execution of several geo-processing functions. Figure 7.1 describes the most relevant steps. The first step applies a kernel function to convert a polygon feature class into a raster file, where a magnitude-per-unit area is assigned to every cell, depending on the density of forest area. In the second step, the raster feature is converted back into polygons regions that

delimit broader forest areas. The create fishnet tool is then used to create an arrangement of points, which are then sampled, selecting for forest locations that fall within the boundaries of the new forest polygon regions.

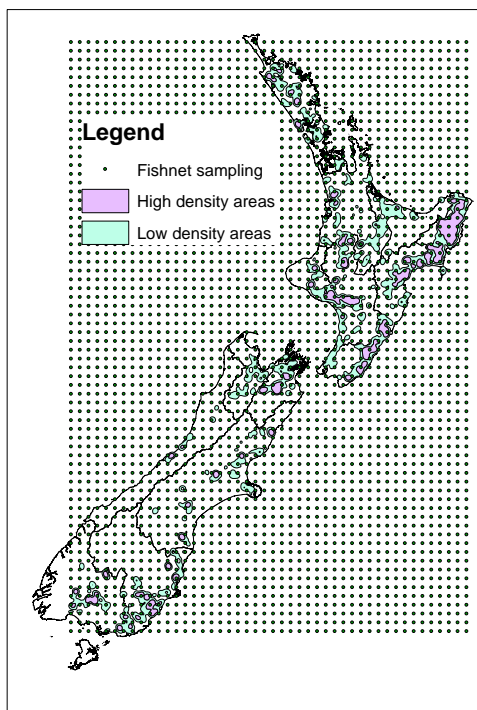




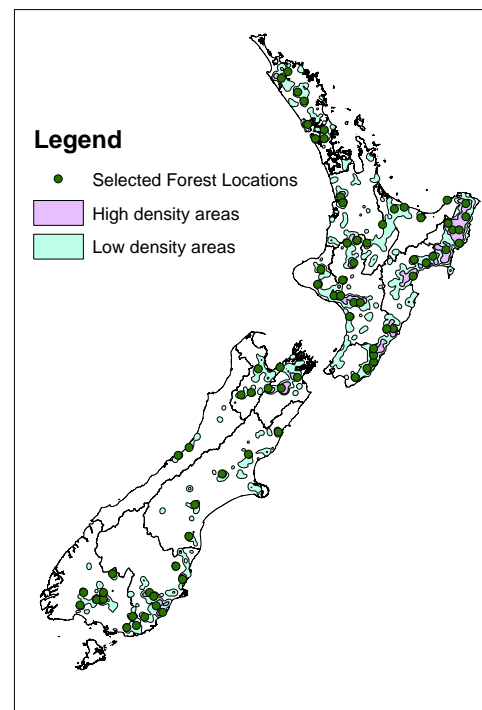
a)



b)



c)



d)

**Figure 7.1:** Forest Sampling Procedure: a) Original LCDB Forest Polygons; b) Binary Raster from application of Kernel Density; c) Polygons representing areas with high forest density and generation of point grid with fishnet; d) Representative points for forest areas

## Notation

$i, j$	<i>regions indexes</i>
$R$	<i>set of regions</i>
$f$	<i>forest index</i>
$p$	<i>port index</i>
$F_i$	<i>subset of forests (<math>F</math>) in region <math>i</math></i>
$P_i$	<i>subset of ports (<math>P</math>) in region <math>i</math></i>
$d_{f,p}$	<i>routed road distance (km) from forest <math>f</math> to port <math>p</math></i>
$a_{i,j}$	<i>log flow (tonnes) from region <math>i</math> to region <math>j</math></i>
$x_{f,p}$	<i>log flow (tonnes) from forest <math>f</math> to port <math>p</math></i>

## Formulation

Regional flows ( $a_{i,j}$ ) were disaggregated into a facility-to-facility ( $x_{f,p}$ ) basis without compromising the original interregional pattern of movements. In the case of log exports, data from the original NFDS table was used to formulate a forests-to-ports LP problem in which the objective function was to minimize the total costs of transportation (5-1), please refer to Appendix B for the Python based implementation of the model. The formulation was based on the assumption that logs are shipped directly between forests to their final destinations (i.e. ports and processing facilities). The transportation costs were calculated from the routed distances by road between forests and ports. The NZ Road Centrelines is available to the public through Land Information New Zealand (LINZ) (LINZ, 2019). The file was used to generate a network dataset after careful topological validation. The cost matrix was obtained through

ArcGIS OD Cost Matrix using a road network dataset and the locations displayed in Figure 7.1.

$$\text{Minimize } Z = \sum_{f \in F} \sum_{p \in P} d_{f,p} * x_{f,p} \quad (5-1)$$

For the supply constraint, the sum of each row was taken as the total production of logs in each region (5-2). This total was allocated evenly amongst the forests that fall within the respective region.

$\forall i \in R$

$$\sum_{j \in R} a_{i,j} = \sum_{f \in F_i \subseteq F} \sum_{p \in P} x_{f,p} \quad (5-2)$$

A similar approach was adopted for the demand constraint, so that, region column totals were allocated amongst the corresponding ports of a given region (5-3).

$\forall j \in R$

$$\sum_{i \in R} a_{i,j} = \sum_{f \in F} \sum_{p \in P_j \subseteq P} x_{f,p} \quad (5-3)$$

A third constraint (5-4) ensured that the inter-regional pattern of flows reported in the NFDS table was maintained between flows from forests-to-ports. Every cell value from the NFDS table represents the total log demand by ports from region  $j$  for logs from forests in region  $i$ . The final constraint (5-5) imposes a lower bound of zero on all variables.

$\forall i, j \in R$

$$a_{i,j} = \sum_{f \in F_i \subseteq F} \sum_{p \in P_j \subseteq P} x_{f,p} \quad (5-4)$$

$$\forall f \in F \wedge \forall p \in P$$

$$x_{f,p} \geq 0 \quad (5-5)$$

## 7.2. Distribution method for dairy exports

Manufactured dairy products represent 25 per cent of the value of total merchandise exports in New Zealand, illustrating the importance of this sector to the national economy (Richard Paling Consulting et al., 2019). The NFDS reports regional movements for dairy products. From the NFDS, it is not possible to discern if the final destination is a port or a retail facility as the tables reported comprise internal movements of product between the manufacturing plants and facilities either for storage along the distribution chain or for completing the process of producing the final product. The distribution model was particularly concerned with dairy exports which were filtered out from the general tables through the sequential application of IPFP and Production-Constrained Gravity Model Calibration. The methods and data sources are reported in this section.

The geographic coordinates of all origins and destinations were extracted through a Google Places API using functionality from the *request* and *json* python based libraries. The process was iterative, queries were composed by elements from lists of city and region names in New Zealand and case-specific keywords including “ports” and “dairy factories”. Queries also included the names of key dairy factories from Fonterra, Westland Milk, Synlait, Open Country, Tatua and Miraka. Similar to section 7.1, routed distances between factories and ports were obtained through ArcGIS OD Cost Matrix.

## Notation

$b_{i,j}$	<i>original dairy movements from region i to region j</i>
$b'_{i,j}$	<i>dairy updated (IPFP) movements from region i to region j</i>
$b''_{i,j}$	<i>estimated dairy movements (for exports) from region i to region j</i>
$\tilde{d}_{i,j}$	<i>average interregional distance between facilities from region i to facilities in region j</i>
$E_i$	<i>cattle numbers in region i</i>
$TR$	<i>row totals vector from dairy movements table</i>
$TC$	<i>column totals vector from dairy movements table</i>
$TM$	<i>total annual dairy exports in tonnes for the base year</i>
$TR'$	<i>updated row totals vector for dairy movement estimation</i>
$TC'$	<i>updated column totals vector for dairy movement estimation</i>
$W_i$	<i>Dairy Exports in port from region i</i>
$k$	<i>gravity model intercept</i>
$\mu$	<i>gravity model origin fixed-effect coefficient</i>
$\alpha$	<i>gravity model destination fixed-effect coefficient</i>
$\beta$	<i>gravity model distance decay coefficient</i>

### Formulation

The first step delivers vectors for row ( $TR$ ) and column ( $TC$ ) totals from the dairy movements table.

$$TR = \left[ \sum_{i \in R} b_{i,1}, \dots, \sum_{i \in R} b_{i,14} \right] \quad (5-6)$$

$$TC = \left[ \sum_{j \in R} b_{1,j}, \dots, \sum_{j \in R} b_{14,j} \right]^T \quad (5-7)$$

Then, the vectors  $TR$  and  $TC$  are normalized, so that the total movements of the updated vectors  $TR'$  and  $TC'$  match the total annual dairy exports in tonnes for the base year ( $TM$ ).

$$TR' = TR * \frac{TM}{\sum_{i \in R} \sum_{j \in R} b_{i,j}} \quad (5-8)$$

$$TC' = TC * \frac{TM}{\sum_{i \in R} \sum_{j \in R} b_{i,j}} \quad (5-9)$$

The original dairy flows ( $b_{i,j}$ ) were updated through the application of IPFP. The script for the IPFP was written in Python programming language. The script used functions from the ‘ipfn’ package, and the inputs were the original table of dairy movements ( $b_{i,j}$ ) and the updated vectors  $TR'$  and  $TC'$ . Please refer to Appendix C for more details on the script. Updated flows ( $b'_{i,j}$ ), the normalized aggregates ( $TC'$ ), the average interregional distances between factories and port locations ( $\tilde{d}_{i,j}$ ), and cattle numbers

by region ( $E_i$ ) were used to calibrate an unconstrained gravity model. For the spatial interaction modelling stage, the ‘SpInt’ module from Python’s Spatial Analysis Library (PySAL) was used as it offers free and open source functionality (Oshan, 2016). The module uses regression techniques to calibrate models. Specifically, it is based on a Poisson log-linear regression specification, which avoids potential issues when dealing with observations with zero flows. Inputs for model calibration are cattle numbers by region ( $E_i$ ), exports by region ( $W_j$ ), a cost matrix ( $\tilde{d}_{i,j}$ ) and a table of observed flows between origins and destinations ( $b'_{i,j}$ ). Cattle numbers by region were obtained from official sources and were the origin attractiveness attributes, as domestic patterns of milk-based products are likely to follow production from the milk industry. An unconstrained and an attraction-constrained gravity formulations were considered, please refer to Appendix D for the python-based implementation of the models. The attraction-constrained formulation kept total exports by region fixed. Equations 5-10 and 5-11 represent the resulting log-linear unconstrained and attraction-constrained gravity models, respectively. The models include an intercept ( $k$ ), an origin fixed effects coefficient ( $\mu$ ), a destination fixed effect coefficient ( $\alpha$ ), a set of destination fixed effects coefficients ( $\alpha_j$ ), and a distance decay coefficient ( $\beta$ ). The final step uses the predicted interregional flows and applies an LP based disaggregation procedure similar to the one described in Section 7.1, using the corresponding OD distance matrices between factories to ports.

$$b'_{i,j_a} = \exp(k + \mu * \ln(E_i) + \alpha * \ln(W_j) - \beta * \tilde{d}_{i,j}) \quad (5-10)$$

$$b'_{i,j_b} = \exp(k + \mu * \ln(E_i) + \alpha_j - \beta * \tilde{d}_{i,j}) \quad (5-11)$$

### 7.3. Distribution method for container imports

The main data source for this section is the table of movements of manufactured goods reported in the NFDS (Deloitte, Richard Paling Consulting, Murray King & Francis Small Consulting, et al., 2014). The direction of flows is opposite to dairy exports, meaning that shipments originate at ports and the final destinations correspond to the facilities from transport and logistics companies throughout New Zealand. The geographic coordinates for the destinations were also extracted through a Google Places API. Queries were composed by elements from lists of city and region names in New Zealand and case-specific keywords including “warehouses” and “transport and logistics”. Queries also included the names of “Toll” and “Mainfreight”, since they are the main transport and logistics companies in New Zealand. Similar to section 7.1, routed distances between factories and ports were obtained through ArcGIS OD Cost Matrix.

#### *Notation*

$c'_{i,j}$	<i>estimated container movements (for imports) from region <math>i</math> to region <math>j</math></i>
$\tilde{d}_{i,j}$	<i>average interregional distance between port from region <math>i</math> to warehouse in region <math>j</math></i>
$V_i$	<i>Container imports in region <math>i</math></i>
$Z_i$	<i>Population in region <math>i</math></i>



## Formulation

The method is similar to the one described in 7.2. Row and column totals were normalized in order to match the total number of imports given in a base year. The normalized vectors were used by the IPFP to deliver a new table. The fitted table was used to calibrate a gravity model using container imports by region ( $V_i$ ) for emissiveness attributes and regional population ( $Z_j$ ) for attractiveness attributes. An unconstrained and a production-constrained gravity formulation were considered. The production constrained formulation kept total imports by region fixed. Equations 5-12 and 5-13 represent the resulting log-linear unconstrained and production-constrained gravity models, respectively. The models include an intercept ( $k$ ), an origin fixed effects coefficient ( $\mu$ ), a set of origin fixed effects coefficients ( $\mu_i$ ), a destination fixed effect coefficient ( $\alpha$ ), and a distance decay coefficient ( $\beta$ ). The final step uses the predicted flows and applies an LP based disaggregation procedure similar to the one described in Section 7.1

$$c'_{i,j_a} = \exp(k + \mu * \ln(V_i) + \alpha * \ln(Z_j) - \beta * \tilde{d}_{i,j}) \quad (5-12)$$

$$c'_{i,j_b} = \exp(k + \mu_i + \alpha * \ln(Z_j) - \beta * \tilde{d}_{i,j}) \quad (5-13)$$

## 7.4. Results and discussion

**Figure 7.2** shows the location of the facilities involved and the layout of the road and railway networks. Interestingly, warehouses and factories seem to be strategically positioned on the vicinity of the railway network. Warehouses also appear to be located on the vicinity of ports. Twelve out of twenty-seven dairy factories are operating within Waikato, as the region

provides a strategic connection between Ports of Auckland (POA) and Ports of Tauranga (POT). The strategic location allows the volumes of full and empty containers to be balanced, as was discussed in Chapter 3.

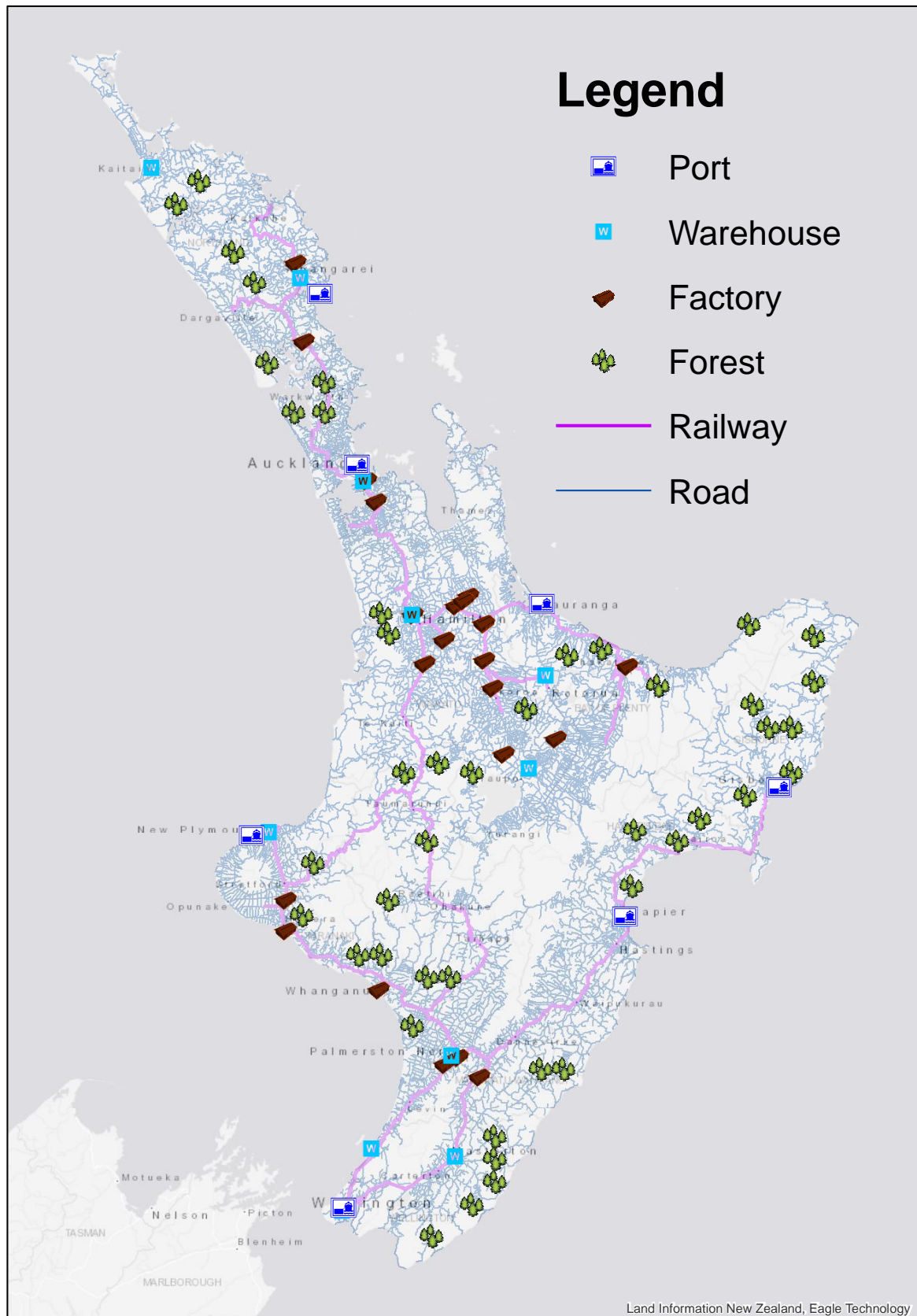
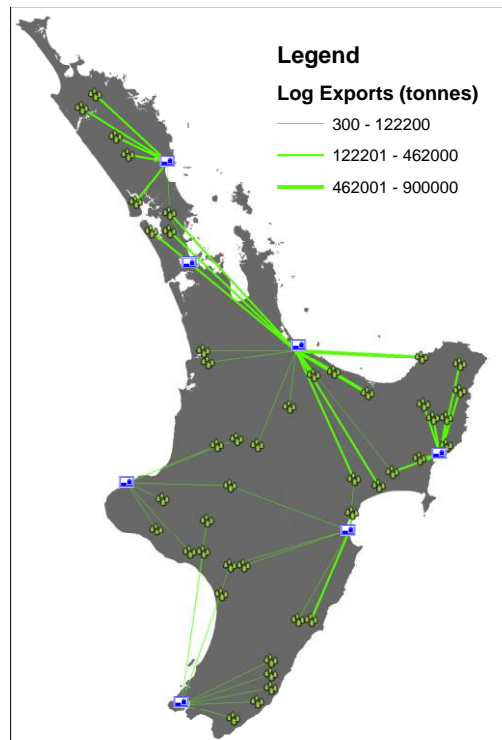
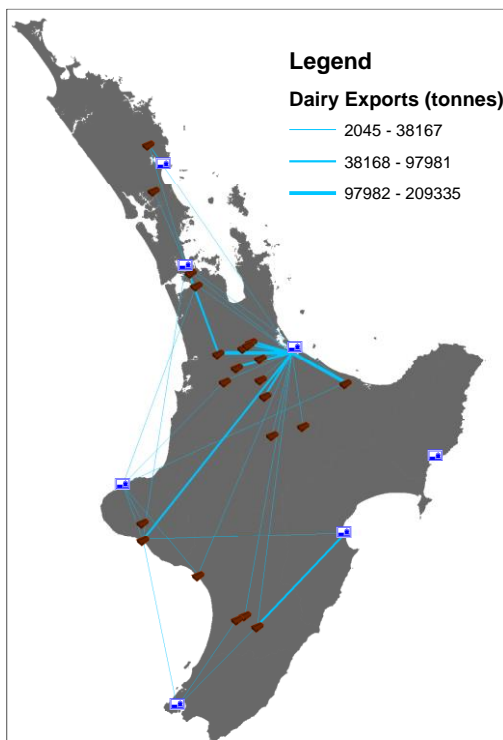


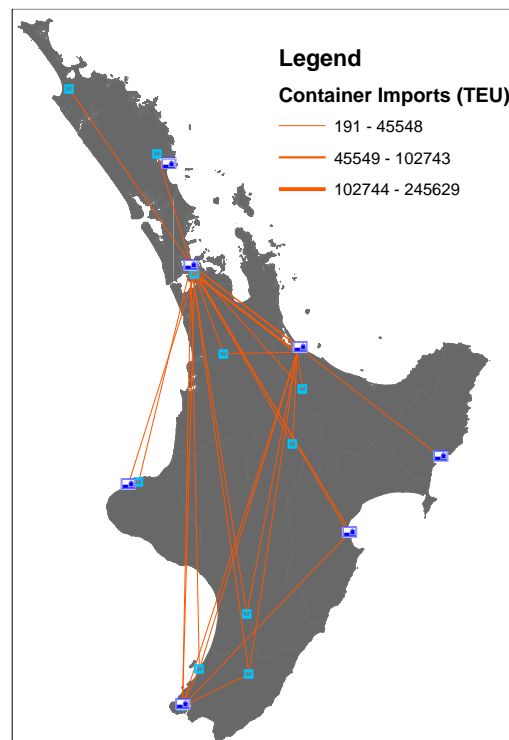
Figure 7.2: Location of entities used for assessment



a)



b)



c)

**Figure 7.3:** Distribution Results: a) Log Exports flows; b) Dairy Exports flows; c) Container Imports flows

Figure 7.3 provides a geographical representation of the results from the application of the freight distribution component. Figure 7.3 (a) shows the pattern of flows for log exports, where activity is concentrated in POT and Northport. Generally, POT appears as the most important port in New Zealand as it handles a significant volume of imports and exports, for bulk and containerized shipments. As for container imports, POA also plays a leading role. Chapter 3 addressed this novel distinction between POA and POT, which have managed to balance the flows through operations at inland terminals like MetroPort. The OD pairs displayed in Figure 7.3 clearly distinguish the roles of POA and POT and evidence the need for inland operations. The distribution models for dairy exports and container imports contemplated the calibration of a set of gravity-based formulations. Table 7.1 shows model fit statistics for different gravity-based formulations. Overall, constrained formulations are associated to higher coefficients of determination ( $R^2$ ), lower errors and lower Akaike information criteria (AIC), denoting better model fit. Specially, there is a notable difference in fit statistics between the formulations for container imports, suggesting that aside from regional population, there might be alternative attributes that can better explain the interaction between warehouses and ports. The dairy export and container import arcs displayed in Figure 7.3 are based on flows predicted with the production and attraction gravity based models, respectively. Matrices associated to these arcs, constitute the main data input for the sequential optimization-simulation approach addressed in the next chapter. The procedure covered by the distribution component allocated representative locations to interregional flows reported in the NFDS. Further disaggregation can be achieved with the execution of the remaining components from STRATCODE, allowing to capture logistic operations between the origins and destinations covered during the distribution model. The assessment has been focused on the North Island because it concentrates most port activity, and it is expected that in the near future there will be major

upgrades and changes on network infrastructure within these regions. More details on potential interventions are discussed in the next chapter.

**Table 7.1: Model fit statistics for gravity based formulations**

Model	R <sup>2</sup>	SRMSE	AIC
Unconstrained gravity for dairy exports	0.79	0.49	514393.8
Attraction constrained for dairy exports	0.85	0.43	358510.4
Unconstrained gravity for container imports	0.74	0.93	306593.7
Production constrained for container imports	0.94	0.32	66874.6

## 7.5. Summary

This chapter described the first component of STRATCODE, a modelling approach that integrates different methods in order to cope with limitations on shipment data availability. The starting point of the distribution component was the geographic representation of the involved origins and destinations. The identification of forest entities was based on a novel approach that used a land-use dataset and several geo-processing scripts to derive representative locations. The location of other entity types was based on the application of web scrapping functions through the use of a Google API. The method integrated by the set of geo-processing scripts can also be of interest to other industries from the agriculture sector, specifically fruit and horticulture industries, as New Zealand has a robust geodatabase that covers land use data for agriculture-based industries.

The methods for modeling transport distribution for different sectors depended on the availability of data. In the simplest case, the distribution of log exports was obtained through the execution of a linear optimization problem. For dairy exports and container imports, the methods combined IPFP, calibration of gravity models and linear optimization. At this stage, the OD pairs delivered from Component 1 do not account for intermediate stops for storage and terminal operations. However, Component 1 allows to assign identification codes and geographic locations to entities or agents that are relevant to this case of study. Moreover, the distribution component setup the data in matrix format which is compatible with the implementation of the forthcoming optimization-simulation approach.

## **Chapter 8: Component 2 – GIS based network analysis model**

Intermodal transportation planning has been gaining attractiveness as a research area that can offer planners the opportunity to design and promote efficient freight transportation with good mobility and reliability (SteadieSeifi et al., 2014). The research field is still emerging and so far, the problems have been tackled from the perspective of Operations Research practitioners (Macharis & Bontekoning, 2004). Model formulations follow the objectives of different decision making levels (strategic, tactic, and operational) (T. G. Crainic & Laporte, 1997). Research on this field has prioritized the viewpoint of carriers and/or shippers rather than on the planning viewpoint that is required in a holistic scheme (Kelle, Song, Jin, Schneider, & Claypool, 2018), limiting the ability to deliver systemic carbon-reducing strategies. The integration of intermodal network planning with GIS has enabled for increased model functionality, usability, and visualization of impacts (J. Winebrake et al., 2008). Furthermore, the focus is shifting towards the development of investment plans aligned with emission reduction goals, so that future networks can be more competent in overcoming environmental constraints and potential limitations on the use of energy resources (Kim, Park, & Lee, 2013).

Component 2 inherits elements from the field of multimodal transportation planning, specifically, from the subset of strategic problems that relate to long term decisions on significant investments to improve the reliability of the network, overcome capacity constraints and improve infrastructure (SteadieSeifi et al., 2014). The conceptualization of a virtual network has led to the development of GIS-based network planning models, which have either been applied to assess trade-offs between different attributes or to identify the optimal location for intermodal hubs (Asuncion et al., 2012; Jourquin et al., 1999; Loureiro & Ralston, 1996; Macharis & Pekin, 2009; J. Winebrake et al., 2008). The contribution of Component 2 relies on its ability to adopt a GIS based network planning model to address multiple objectives

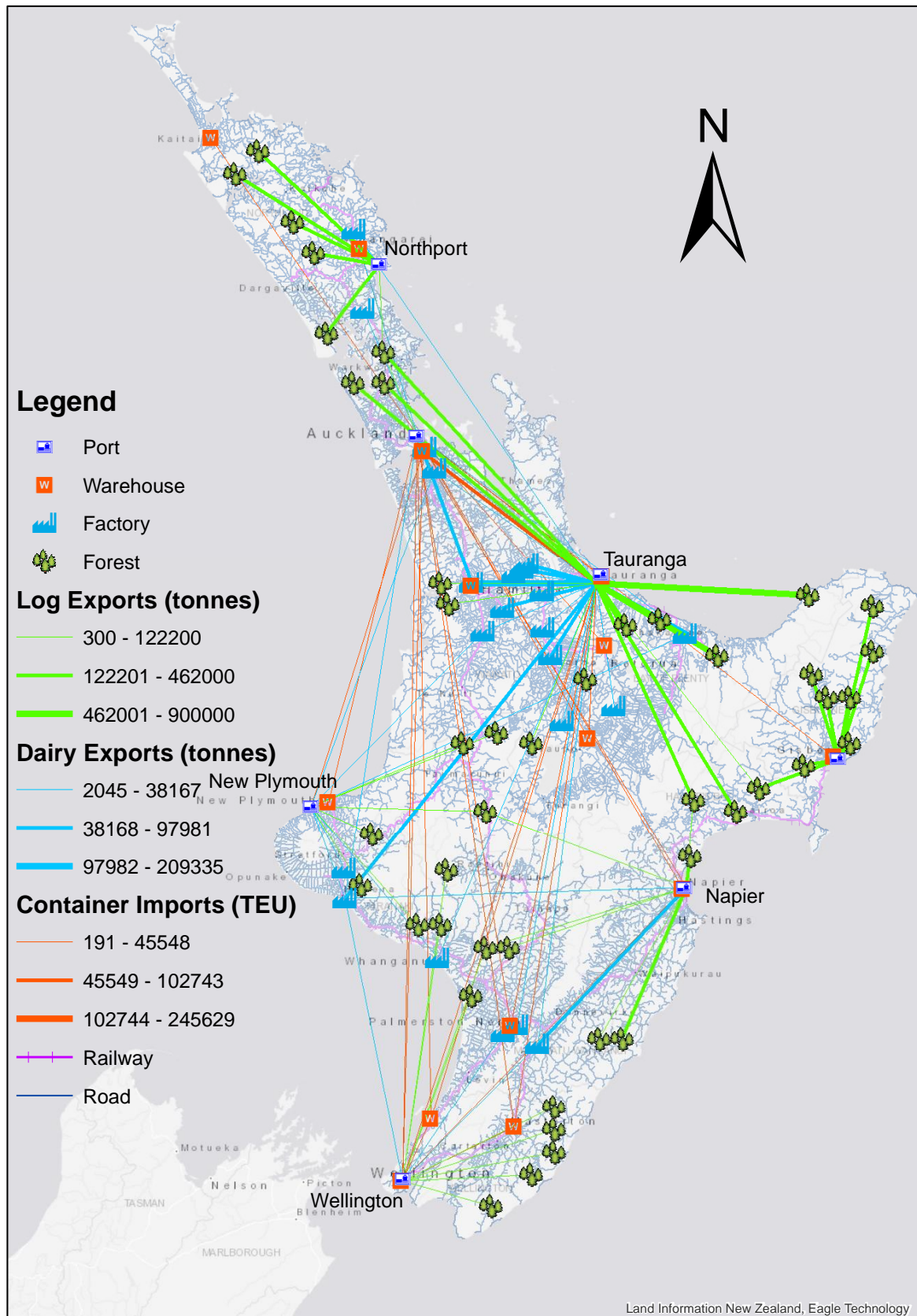


including: allocate mode and route choice to different shipments, weigh network traffic under different scenarios, select the locations for intermodal terminals, generate a database of shipping plans for several OD pairs. Chapter 8 describes the use of OD matrices delivered from the first component and also covers the construction of a multimodal network and the formulation of the model's algorithm. The model uses New Zealand's North Island as a case of study and is implemented for different scenarios, including cost and energy use optimization, shift in port activity, and extension of the railway network. Average trip time, energy demand and GHG emissions are used as key performance indicators. Altogether, component 2 establishes the foundations of a long-term concept, allowing for the identification of the network arrangement that delivers the least transport energy demand through the adoption of multimodality.

## 8.1. Data Sources

**Figure 8.1** gives a representation of the main model input, a set of line feature classes representing export (dairy, log) and import (general containerized freight) flows within the North Island. Every row of the corresponding attribute tables contained data on a specific OD pair including identification strings for origins and destinations and annual flow between them. Flows were derived upon a programmatic application of linear programming (LP), iterative proportional fitting procedure (IPFP) and calibration of spatial interaction models. More details on the method were provided in Chapter 7. The multimodal network addressed in Section 8.2 is made up of roads, rail spurs and transshipment points with corresponding distance, time and energy use attributes. Energy use calculations used energy intensities reported in previous studies and in Lipasto unit emissions database (Asuncion et al., 2012; Lipasto, 2017a; J. Winebrake et al., 2008).

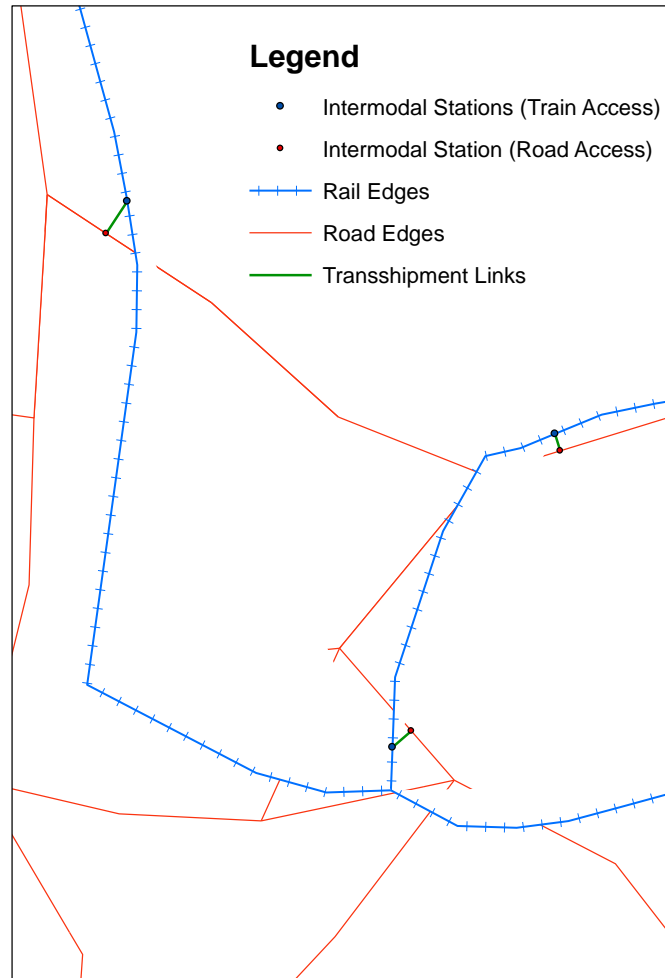
Road links are based on the NZ Road Centrelines file available to the public through LINZ (LINZ, 2019). Railway links and stations were obtained through KiwiRail's open source GIS data platform (KiwiRail, 2018). The GIS environment managed feature datasets based interchangeably on the WGS84 geographic coordinate system and on the NZGD 2000 New Zealand Transverse Mercator projection. The reason for choosing WGS84 coordinate system is its adoption by standard platforms like GPS and Google APIs. The use of a local projection enhanced convenient manipulation of distances in metric units. Train stations displayed on **Figure 8.1** have been verified to have more than one track and are considered as candidates for intermodal hub selection. Aside the geographic representation of the network, **Figure 8.1** also shows a contrast between import and export volumes for Ports of Auckland (POA) and Port of Tauranga (POT), respectively. Moreover, Northport appears as a strategic location for log exports.



**Figure 8.1:** Data sources and freight distribution

## 8.2.Methodology

This section presents the algorithm for a network design model with an embedded shortest path solver. Appendix F provides the python implementation of the model described in this section. The network model takes a set of line feature classes (OD matrices), point feature classes (origins and destinations) and multimodal network datasets as inputs. Before actual model execution, a multimodal network dataset was built using ArcGIS Desktop 10.6. During the building process, network elements are created, connectivity is established, and attributes are assigned to every type of link. A total of 109 transshipment links were created using functionality from ArcGIS Analysis Tools. Specifically, the *Near* function calculates distance and additional proximity information between the input features (train stations) and the closest point in another feature class (road network). The *Near* function delivers the coordinates of the point features located on the road network that are closest to the given set of train station points, and a new point feature class was created upon these coordinates. The transshipment links are line features that connect the points representing train stations with their corresponding closest points located on the road network, Figure 8.2 illustrates the result of the process.



**Figure 8.2:** Generation of transshipment links

Specifically, the creation of the multimodal network dataset involves the participation of the feature classes displayed in Figure 8.2, which are connected to each other upon the definition of specific connectivity policies. Road, rail and transshipment edges were assigned distance, time and energy use attributes associated to each transportation mode. Coastal shipment was omitted from the analysis, as the current modal share is small, approximately 4% (Richard Paling Consulting et al., 2019). Moreover, the geographic scope of the case study leaves out inter-island movements, where coastal shipment would have been more relevant.

For rail and road edges, time was estimated to be a function of routed distance, given average speeds of 30 km/h and 70 km/h, respectively. Transshipment time was assumed to be fixed, given a value of 5 minutes per each tonne transferred. Energy use was also estimated as a function of routed distances. Energy intensities were obtained from Lipasto database, assuming a partially loaded semi-trailer combination for road transport (0.74 MJ/tkm) and a diesel driven container train for rail transportation (0.24 MJ/tkm) (Lipasto, 2017a). Energy demand for transshipment operations was assumed to be fixed, with a value of 1.58 MJ per tonne transferred, which was derived from previous studies assuming an average weight of 12.7 tonnes per TEU (Asuncion et al., 2012; J. Winebrake et al., 2008). Table 8.1 presents values used in the calculation of energy and travel time attributes for road and rail transport operations. Table 8.2 presents values used in the calculation of energy and time attributes for transshipment operations

**Table 8.1: Values used in energy and travel time calculations for transportation operations**

Operation	Energy Intensity (MJ/TKM)	Cruise Speed (km/hr.)
Rail Transportation	0.24	30
Road Transportation	0.74	70

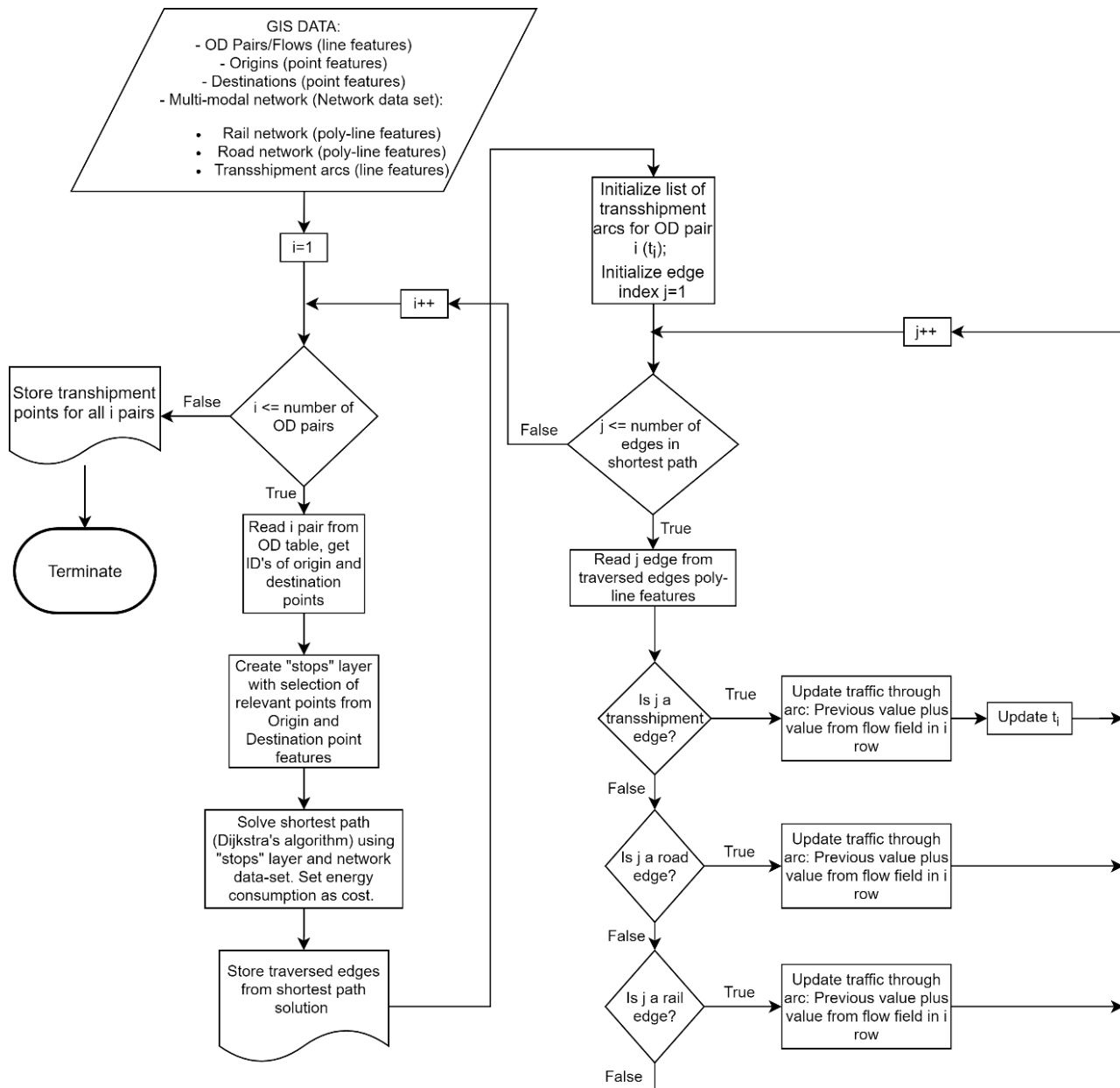
**Table 8.2: Values used in energy and time calculations for transshipment operations**

Operation	Energy Intensity (MJ/tonne)	Time (min/tonne)
Transshipment	1.58	30

Origin and destination nodes were represented by a group of ports, terminals, factories, warehouses and material extraction facilities.

Figure 8.3 presents the model's algorithm. It was coded in Python 2, using network analysis functionality from the Arcpy library. Network Analysis identifies an optimal path through the execution of Dijkstra's algorithm, which is executed for every OD pair using either energy use or travel time as cost attributes. Appendix E provides a brief explanation of the logic behind the shortest path algorithm and the corresponding python implementation (Dijkstra, 1959).

The links (road, rail and transshipments arcs) that integrate every solution or shortest route are assigned the corresponding traffic volumes. The model output is integrated by three line feature classes representing road, rail and transshipment edges respectively. Every edge in the solution has a traffic attribute associated to it, representing annual flow under the optimal scenario. Moreover, for every OD pair a shipping plan is generated and recorded, containing information on origins, destinations, mode allocation and transfer nodes. The model output also allows to identify train stations that can become intermodal hubs and road arcs with enough traffic to justify spur extensions from the railway network. Train routes and frequencies are arranged upon the traffic estimates and tested during simulation.



**Figure 8.3:** GIS based network model algorithm

The verification process was mostly concerned with the assessment of network topology rules. For model validation, total imports and exports by ports were compared against the resulting tonnes assigned to transshipment edges connected to port features. The idea was to confirm that the model constraints were being fulfilled.



## **Rationale for scenario selection**

According to a recent report published through the Ministry of Transport, future operation of POA is not economically or environmentally viable, and it is constrained by landside infrastructure failure. The report also recommends that Northport should be developed to take over much or all of Auckland's existing and projected future freight business (North Island Supply Chain Strategy Working Group, 2019). In line with these recommendations, the network model is executed for different scenarios, allowing to assess the impact of changes in the pattern of shipments and network layout. Moreover, scenarios consider different optimization criteria to contrast trade-offs between delivery times and energy demand. Table 8.3 shows the conditions and corresponding codes used for the construction of different scenarios. In regard to the pattern of flows, two cases were considered: Business as Usual (BAU) and Full Shift (FS). In the BAU case, the current pattern of flows is maintained and POA remains operational. Under the FS case, all activity is shifted from POA to Northland. The current railway network does not have a connection to Northport. The model is executed with (WC) and without a railway connection (NC) to Northport. Finally, the execution of the network model considers two attributes for optimization, Energy use (E) and Travel Time (T). The results in Section 8.3 cover a range of six scenarios that are based on a combination of the aforementioned interventions.

**Table 8.3: Codes and conditions for scenario construction**

<b>Code</b>	<b>Description</b>
<b>BAU</b>	Business as Usual
<b>FS</b>	Full Shift to Northport
<b>WC</b>	With rail connection to Northport
<b>NC</b>	No rail connection to Northport
<b>E</b>	Energy use optimization
<b>T</b>	Travel time optimization

### **8.3.Results and Discussion**

The model was executed given six different scenarios:

- BAU-NC-T: Business as usual, no rail connection to Northport, Travel time optimization
- FS-NC-T: Full shift to Northport, no rail connection to Northport, time based optimization
- FS-WC-T: Full shift to Northport, with rail connection to Northport, time based optimization
- BAU-NC-E: Business as usual, no rail connection to Northport, energy use optimization
- FS-NC-E: Full shift to Northport, no rail connection to Northport, energy use optimization
- FS-WC-E: Full shift to Northport, with rail connection to Northport, energy use optimization

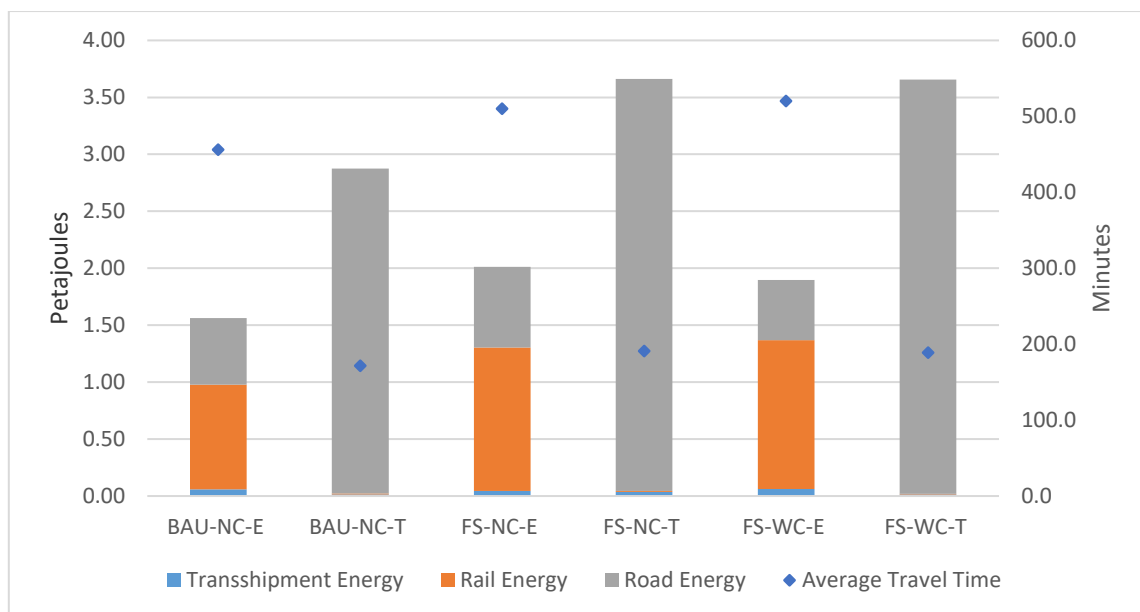
In every case, mode and route selection are carried out in a deterministic way, aiming to minimize either energy use or travel time. Energy use and average travel times for each scenario are reported in Figure 8.4. Scenarios that show more reliance on road shipping are associated to time-based optimization (BAU-NC-T, FS-NC-T and FS-WC-T), resulting in shorter travel times. On average, scenarios where energy use was optimized are associated with travel times 170% higher than those of time-based optimization scenarios. In contrast, scenarios where travel time was optimized have 86% more energy demand than scenarios based on energy use optimization. There is an evident trade-off between travel time and energy use. A major investment in freight transport infrastructure can enhance a system where rail has a dominating role. However, the availability of intermodal infrastructure does not guarantee that all stakeholders involved, including shippers and producers, will be committed to compromise just-in-time shipping at the expense of environmental concerns. Consequently, it is likely that an aspiring investment plan would need to be accompanied by policy instruments that could regulate the environmental externalities associated with trucking.

Figure 8.1 shows that POA is currently a strategic gateway for overseas imports. It is through POA that containers enter New Zealand and are subsequently delivered to regions across the country. Overall, a full shift to Northport would imply longer distances between the port and final destinations and subsequently would lead to higher energy demand. This aspect is reflected in Figure 8.4, as scenarios that resemble a full shift to Northport (FS), have a higher total energy consumption than the Business as Usual cases (BAU) with POA fully operational. If the shift to Northport becomes effective, it is evident that there would be an urgency to develop infrastructure that can mitigate the potential increase in energy demand. Figure 8.4 also provides insights on plausible impacts of a full shift. If there are no interventions on

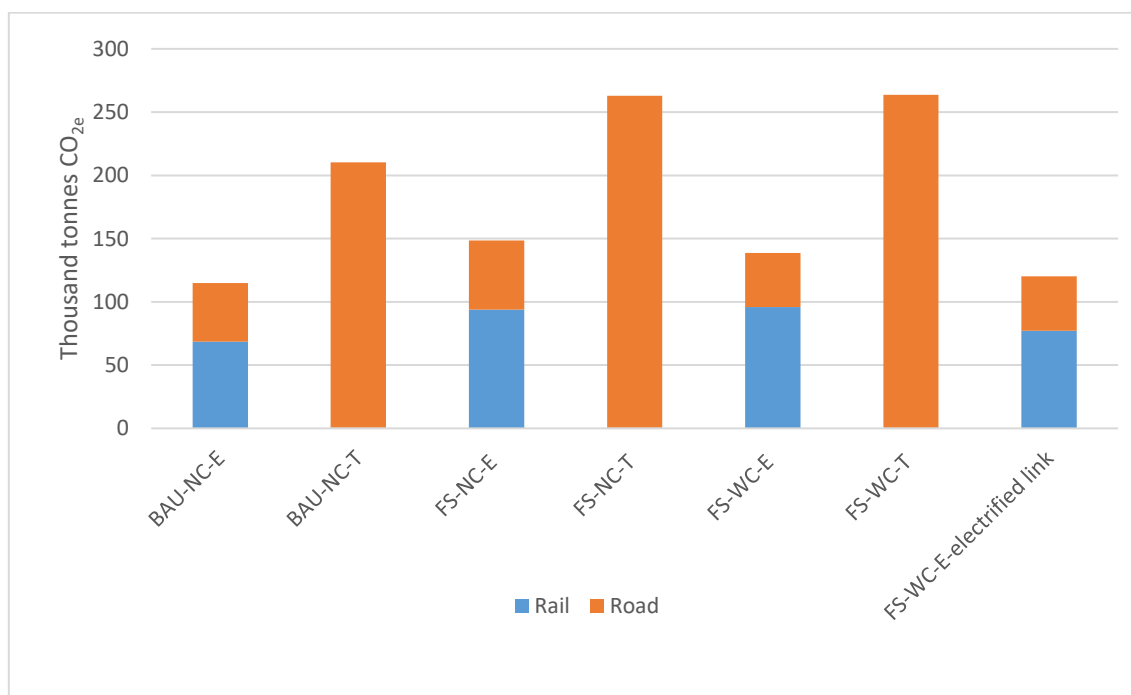
infrastructure and trucking remains the dominant mode of transportation, energy demand could increase by 86% in the worst case scenario (FS-NC-T).

The energy planning model presented in Chapter 4 was used as an emissions calculator. Figure 8.5 shows total direct and indirect emissions for all scenarios, including an additional one (FS-WC-E-electrified link) that considers the electrification of the trunk rail line that runs from Auckland to Moerewa. Overall, it can be seen that emissions are proportional to energy demand as expected. Given the case that a full shift to Northport takes place and trucking remains the dominant mode, GHG emissions can reach up to 250 thousand tonnes of CO<sub>2e</sub>. Comparing the FS-NC-T and FS-WC-E scenarios, a significant shift to rail represents a 47% reduction in total GHG emissions. Given New Zealand's current grid composition and resource availability, if the trunk line above Auckland is electrified, an additional 7% reduction could be achieved at the expense of 29 additional Megawatts in peak power requirements. It would be important to test the cost effectiveness of the electrification pathway as most of the reduction in emissions will be owed to a modal shift from truck transportation. For this case of study, in the best case a 54% reduction in gross emissions is feasible but is still not enough to meet the national 2050 target of a 70% reduction. Under these circumstances, it is likely that there is a need for additional interventions beyond a substantial transformation in network infrastructure.

The main motivations behind the move to Northport are congestion within the city of Auckland, which drives inefficiencies throughout the local supply chains, and the redevelopment of the waterfront in the central business district. It is expected that a shift to Northport will alleviate current congestion levels, and will also enhance land use transformation, potentially allowing port land to achieve higher returns than the current port's dividends (North Island Supply Chain Strategy Working Group, 2019).



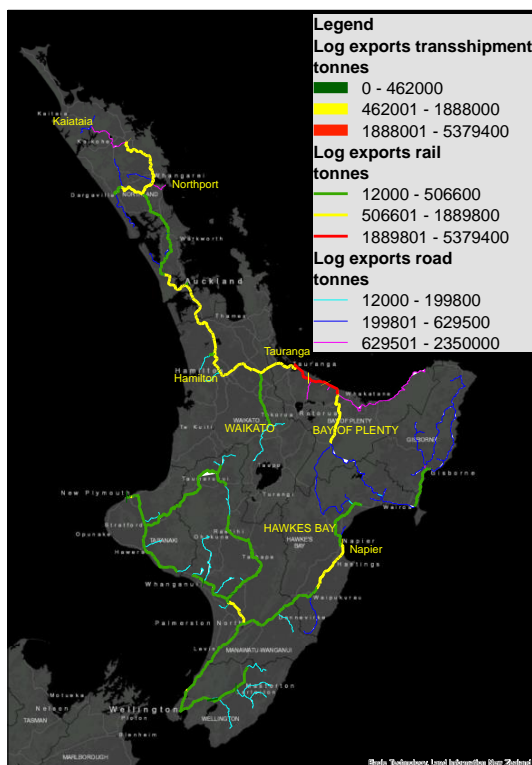
**Figure 8.4:** Energy demand and average trip time for different scenarios



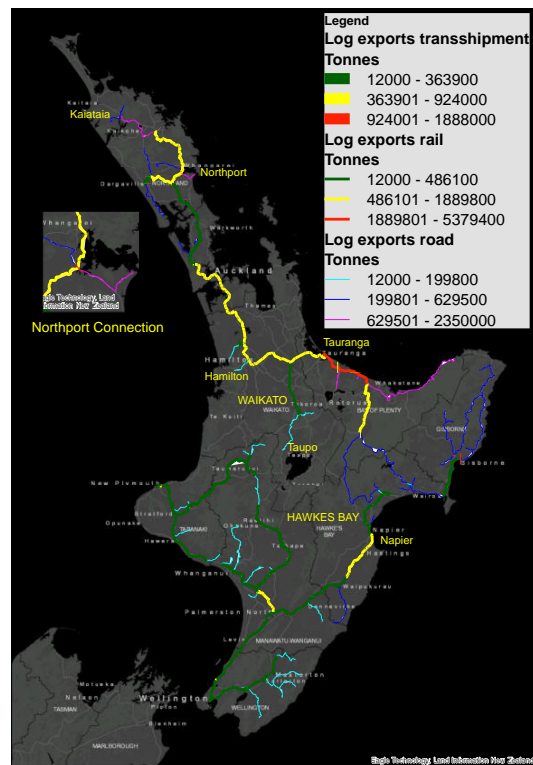
**Figure 8.5:** Direct and indirect GHG emissions for different scenarios

Figure 8.6 shows traffic assignment throughout the network for exports where energy was used as a cost attribute. It can be seen that the relocation of POA, relieves some of the traffic around

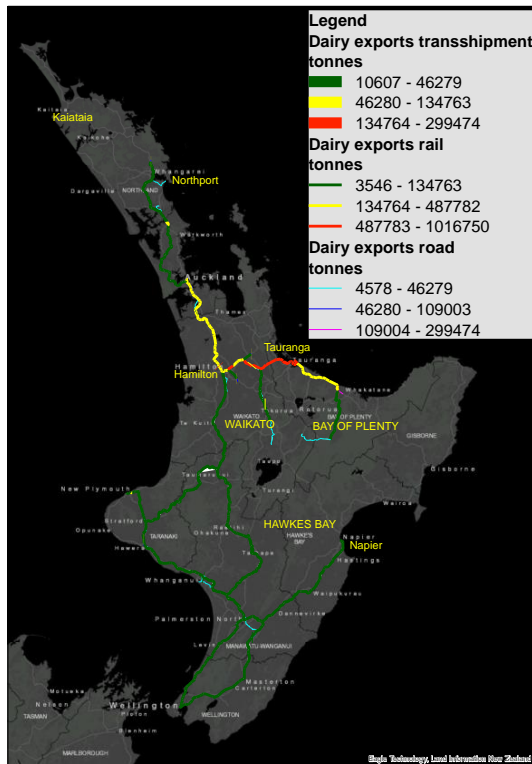
Auckland, and increases congestion levels on the links connecting to Northport. For the current pattern of flows (BAU), traffic is concentrated across the regions of Auckland, Waikato and Bay of Plenty. Hamilton appears as a key location as it provides a strategic connection point between POA and POT. Moreover, there are road segments with significant traffic, where railway tracks could be deployed and take advantage of economies of scale. This is the case of road segments connecting to Kaiataia in the Northland Region and Taupo in the Waikato Region. Despite the railway connection to Gisborne, the port seems to require an alternative and more direct route to the Bay of Plenty Region.



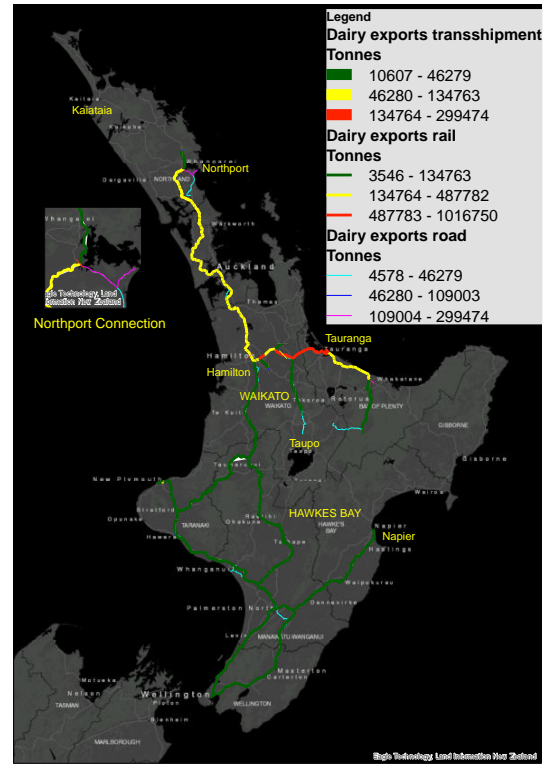
a)



b)



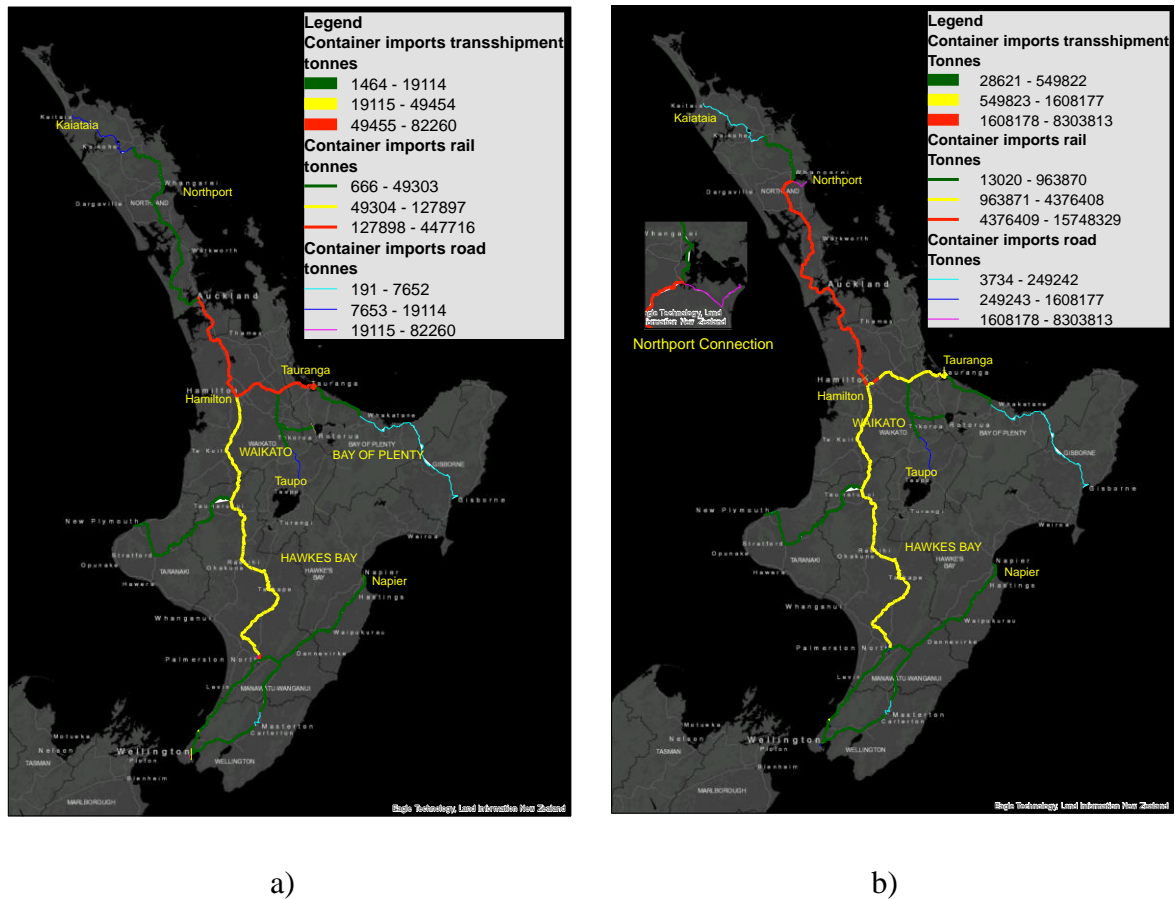
c)



d)

**Figure 8.6:** Road and rail movements for log exports in (a) BAU-NC-E and (b) FS-NC-E scenarios, and dairy exports in (c) BAU-NC-E and (d) FS-NC-E scenarios.

Given a relocation of the port, Figure 8.7 shows that the railway segment north of POA can potentially become a bottleneck for the movement of container imports. The capacity of this section can be enhanced through upgrades in railway infrastructure, double tracking, and deployment of intermodal railyards. The traffic estimates from the network model output allows to identify the service lines and train frequencies that would be required to meet the freight demand within the region. The train frequencies are confirmed during the simulation step, as the operational capacity of the railway system also depends on the performance of loading and unloading operations at the terminals.

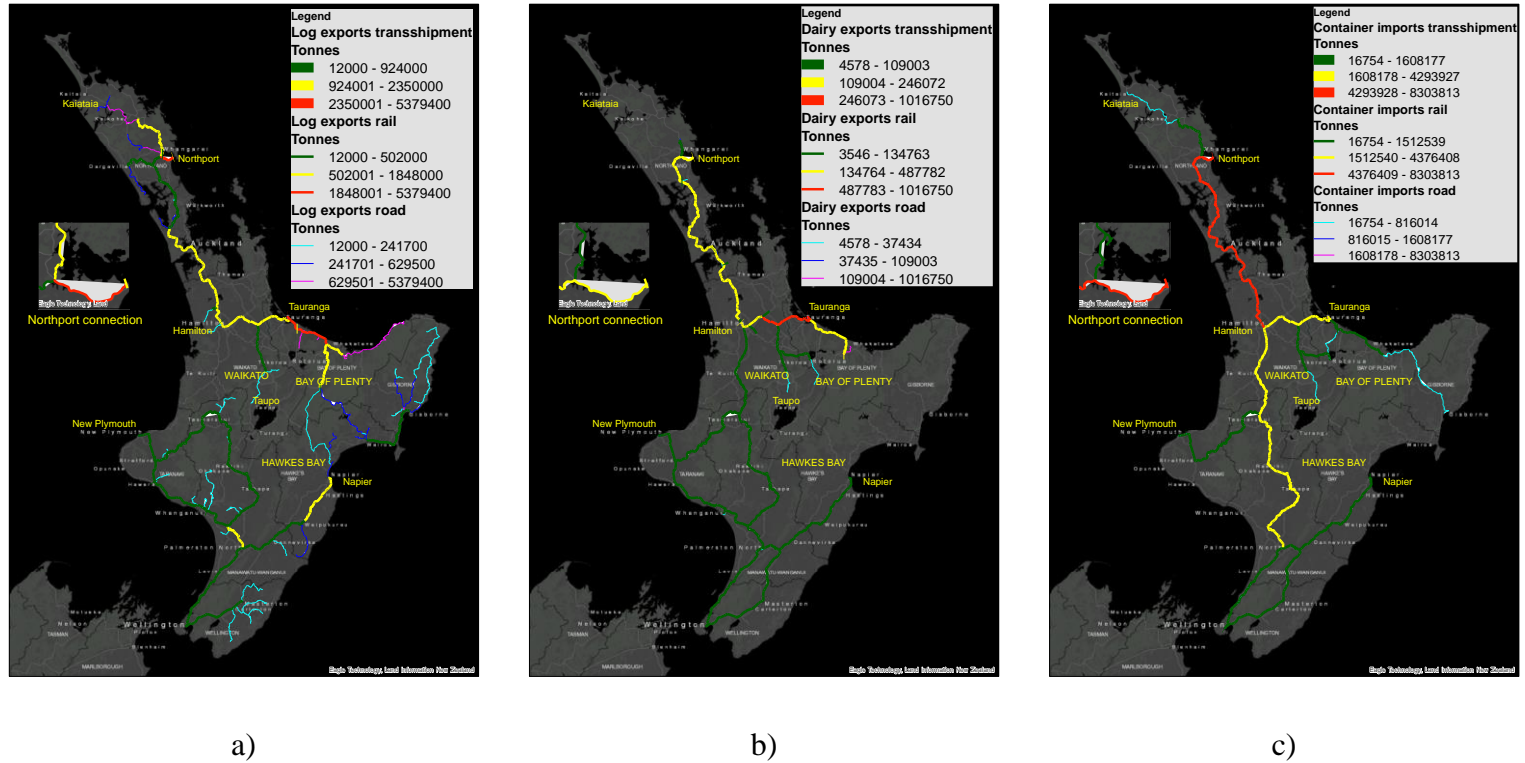


**Figure 8.7:** Road and rail movements for container imports in (a) BAU-NC-E and (b) FS-NC-E scenarios.

Figure 8.8 shows the results when including a direct rail connection to Northport. The long-run rail route can lower energy demand even further and reduce road congestion in areas in the vicinity of the port. The traffic estimates shown in Figure 8.8 can be useful when assessing network capacity, as the geographic and topological layout of the simulation model is based upon these estimates. The assessment also allows to identify the most suitable locations for the development of intermodal hubs. According to the results, 46 out of 109 hub candidates were selected in the best case scenario (FS-WC-E). The model provides details on the type and volume of freight handled at each hub, hence this information is used during the simulation



step to assess the resources that would be required depending on the type of commodities to be handled at the terminals.



**Figure 8.8:** Network traffic through different modes, energy as a cost attribute: (a) Log Exports under FS-WC-E; (b) Dairy exports under FS-WC-E; (c) Container imports under FS-WC-E.

## 8.4. Summary

This chapter described the second component of STRATCODE, a GIS-based multimodal network model. The methodology covered the construction of a multimodal network using a set of point (train terminals) and line (road, railway and transshipment links) features, mode specific attributes (energy intensities and travel speeds) and setting connectivity rules. The methods also contemplated the formulation of the model's algorithm, where a set of matrices

was taken as an input for the execution of a shortest-path optimization for every OD pair, leading to the allocation of route and mode choice for every shipment. The output consisted of a set of road, railway and transshipment edges with traffic attributes for different commodity types. A central feature of Component 2, and to the whole STRATCODE framework, is the application of the traffic assessment as an instrument to build a database with optimal shipping plans and also to identify a subset of terminal locations, whose capacity is to be interrogated during simulation. The model was implemented for six different scenarios, exploring different optimization criteria, a shift from POA to Northport, and an upgrade on the railway network. The results evidence a trade-off between travel time and energy use. Assuming that scenarios that prioritize travel time over energy consumption represent the status quo, where trucking is the dominant mode, a substantial investment in intermodal infrastructure can potentially foster reductions of 48% and 47% in energy demand and GHG emissions, respectively. The electrification of a railway corridor with significant traffic can enhance a further 7% reduction in emissions. Yet, the estimates still fail to reach the 70% reduction target, suggesting the need to reassess the essentiality of the commodities being moved throughout the transportation network.

## Chapter 9: Component 3 – GIS-based discrete event simulation model

The application of multimodal network analysis enables the prediction of traffic associated with different scenarios. In this section, a GIS-based discrete event simulation model is adopted to enhance the analytical solution based on the *best-case scenario* reported in Chapter 8: a full shift in freight activity from Auckland to Northport with a direct railway connection to the port and shipment routes based on energy use optimization.

Regarding the freight-modelling domain, simulation-based modelling is still a recent approach that is building upon inherited structural components from multi-agent supply chain dynamic models (Baindur & Viegas, 2011; Holmgren et al., 2012; V. Reis, 2014; Swaminathan et al., 1998). Furthermore, recent approaches have coupled simulation models with GIS features to reliably estimate cost and supply chain performance parameters (Sahoo & Mani, 2015).

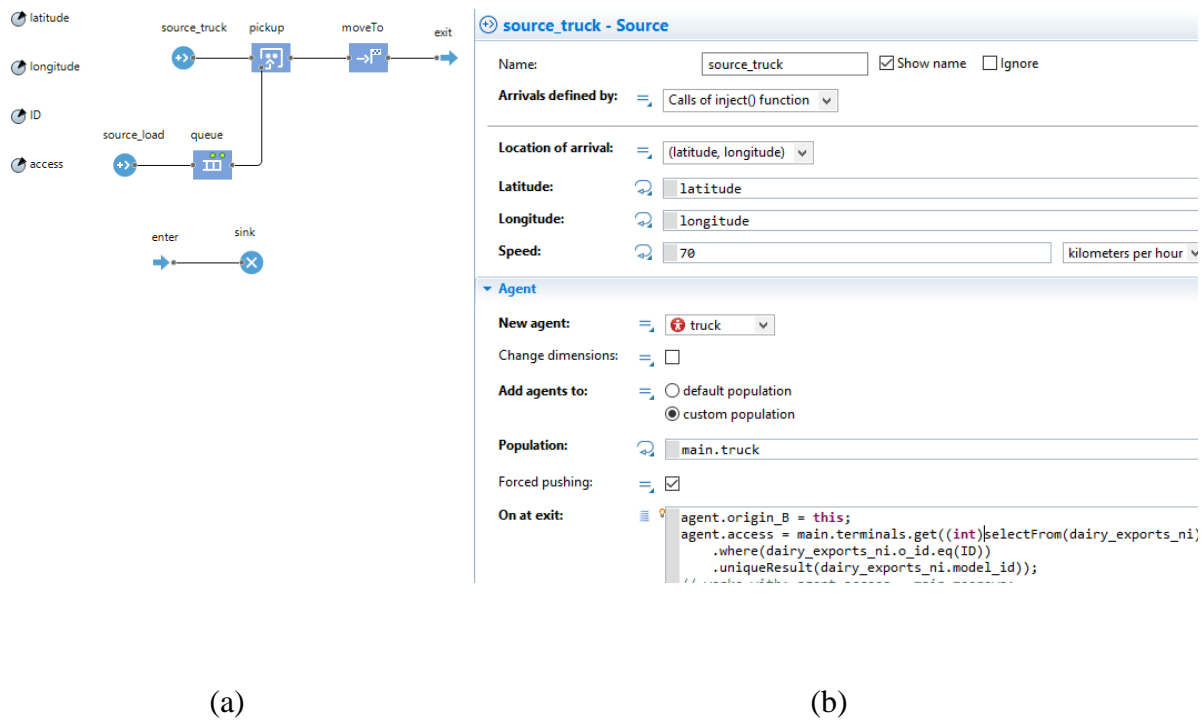
The simulation method covered in this section addresses some limitations from conventional freight models (Liedtke, 2009), by capturing logistics and behaviour-oriented policies and effectively characterizing the heterogeneity of actors and objects in freight chains. Component 3 embraces a GIS-based simulation model to ascertain the capacity needed to run a fully intermodal system, using the upper North Island of New Zealand as a case of study. Moreover, Component 3 is novel because it connects network design, train scheduling, terminal and hauling operations, and it interrogates the capacity and resources needed to run a fully intermodal system.

The model developed within this section is used in different simulation experiments that assess system performance and streamline a network concept in terms of layout, terminal resources and investment costs.

## 9.1.Methodology

The model for component 2 was created with Anylogic 8.5.2 software. Anylogic was particularly useful as it integrates GIS maps and to build networks from shapefiles. The software offers a multimethod environment that combines discrete event, agent-based and system dynamics methods. Moreover, it has specific libraries that allow simulation and visualization of precise operations of railway systems, manufacturing and warehouse workflows. Within the field of freight transport, Anylogic's agent-based functionality has been used to assess logistics performance in response to collaboration protocols between supply chains (Sarraj et al., 2013). Studies on the field have also used the software to conceptualize communication amongst agents in the form of contracts, accounting for the impact of market dynamics on agent behaviour (Baindur & Viegas, 2011; V. Reis, 2014).

The simulation module contemplates train, truck, forest, factory, and terminal agents interacting within a GIS space in response to shipping orders defined through rates. Orders are sourced from factories, forests, and ports. Rate values are obtained from a database through queries containing information on the origin and destination of the shipment and on the type of commodity to be transported. Once a shipping order is sourced, a transportation service is arranged. Figure 9.1 illustrates the logic behind sourcing orders and transportation services within factories. Every factory agent has parameters including the geographic coordinates, identification code and the hub assigned for a shipment (access). In Figure 9.1(a) a shipment order is sourced, then assigned a truck agent and moved to either a final destination or an intermodal hub.



**Figure 9.1:** Workflow for factory logic: (a) Workflow; (b) Code executed under source block

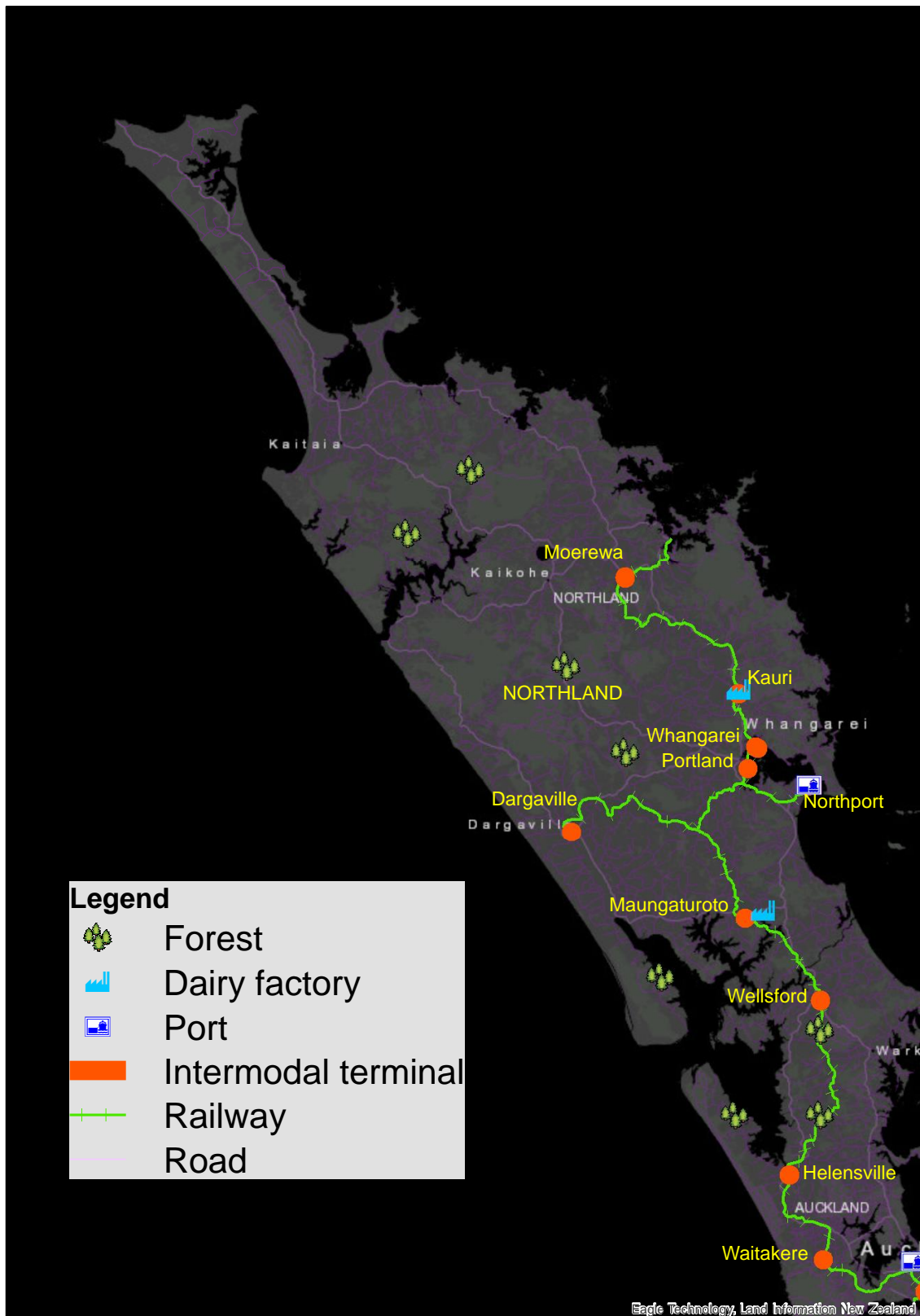
Depending on the location of the facility and its accessibility to the railway network, three services are considered: truck only, intermodal and rail only services. Shipping plans generally involve intermodal trips based on connections also extracted from a database. Figure 9.1(b) shows the code to be executed when a truck agent leaves a source block. The code assigns an origin and an intermodal hub to the truck agent. The assignment of an intermodal hub is carried out through a query, which retrieves information on the location of transshipment points. By default, Anylogic offers routing functionality, allowing agents to move through road and railway networks based on data extracted from OpenStreetMap servers. However, the simulation model was based on an upgraded railway network with a direct connection to Northport. A customized network was built upon a shapefile previously edited in ArcMap. Loading and unloading operations take place at intermodal terminals and their performance is contingent on the operation time and availability of resources (cranes and forklifts). Operations simulated at terminals are limited to the logistics side, capturing the interactions between

trucks, trains and loading equipment, and subsequent repercussions on the broad freight system. The scope of the model does not contemplate yard and storage planning as is the case of other simulation models that focus solely on terminal operations (Cartenì & Luca, 2012). Daily train services are simulated, the routes and frequencies are derived by the traffic estimates from the optimization module. The model shows used railway capacity, that is, it reflects potential traffic and varies with changes in infrastructure and operating conditions (Abril et al., 2008). Particularly, railway capacity is ascertained from upgraded double track network segments, train speed, and terminal performance (stop times).

The network layout for the simulation accounts for the operation of intermodal terminals selected upon the execution of the network assessment (Component 2). Eight intermodal terminals were considered from North to South they are: Moerewa, Kauri, Whangarei, Portland, Dargaville, Maungaturoto, Wellsford, Helensville and Waitakere. Figure 9.2 displays the terminals along with other entities or agents considered for the simulation model, including forests, port (Northport) and factories. Figure 9.4 provides the logical representation of the railway network, which corresponds to the upper part of the North Island. The workflow uses Anylogic's symbology and has embedded functions and auxiliary variables that coordinate train movements within the network. For instance, for every section that is comprehended between terminals, there is an auxiliary Boolean parameter that when set to *True* blocks the movement of trains in opposite directions when the section is considered to be single tracked. Terminals have similar functionality because intermodal operations are allowed on all of them. However, they do not necessarily provide the same service, as some of them only handle a specific type of commodity or serve specific train lines.

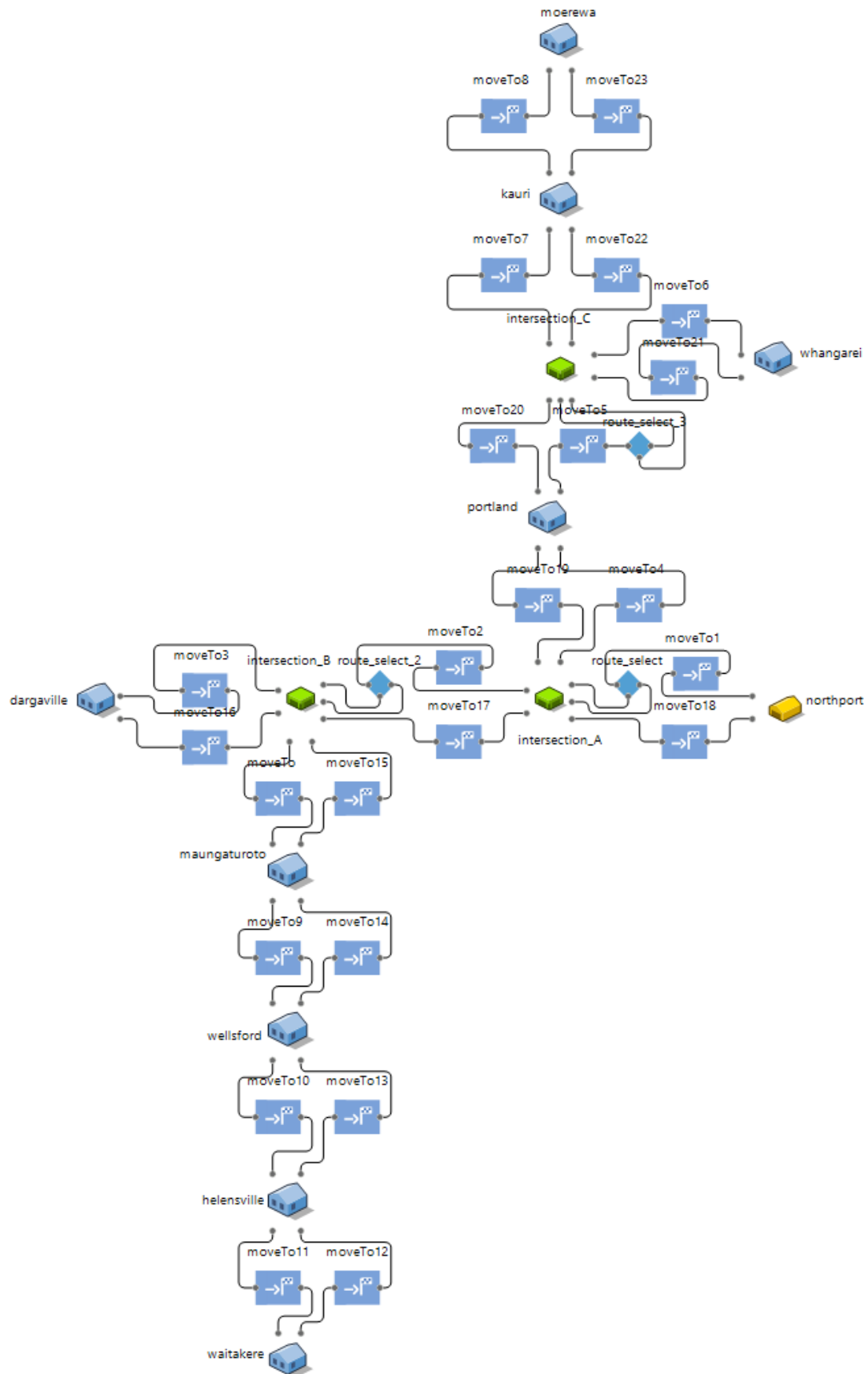
The traffic assessment represented in Figure 6.9 allowed for the identification of six train services. Line 1 is dedicated to carry imported containers from Northport to Waitakere, an

inland terminal located on the northern outskirts of Auckland. Trains returning from Waitakere pick up export logs from Helensville and Wellsford, and dairy exports from Maungaturoto. Line 2 is fully dedicated to carry export logs from Dargaville to Northport. Lines 3 and 5 are dedicated to carry imported containers from Northport to Moerewa and Whangarei, respectively. On the way back, lines 3 and 5 pick-up log and dairy exports from stations located on the way to Northport. Line 4 is fully dedicated to carry export logs from Portland to Northport. Line 6 picks up dairy exports from Kauri and on the way back to Northport picks up export logs from intermediate stations. Once a train enters a terminal, a new workflow is applied, similar to that shown in **Figure 9.4**, where every train is monitored and assigned specific loading or unloading instructions. Terminals are programmed to allocate distinct workflows depending on the type of load carried by trucks entering their premises. The programmatic allocation of workflows was enhanced through the implementation of java interfaces. Interfaces allow to execute generic functions on different terminals. For instance, a *take* function instructs a terminal to allow a truck agent to enter and unload a shipment. The interpretation of the function depends on the type of terminal, as there are specific workflows for different commodity types.



**Figure 9.2:** Area of study for simulation model





**Figure 9.3:** Simulation model main layout - logical representation

**Figure 9.4** presents a general workflow for a terminal agent. The workflow connects a network of service nodes consisting of queue and server blocks (Leemis & Park, 2006). A train enters a terminal and is assigned a track element from a collection of tracks representing a railyard. The number of tracks at each railyard is exaggerated, as the goal of the simulation is to precisely determine railyard utilization and to fine-tune railyard arrangement in order to deliver the number of tracks needed to guarantee continuous operation of the system. If cargo needs to be unloaded, a crane is seized from a pool of crane resources. Unloading times are simulated through delay blocks. Cargo is unloaded from the train and placed on a storage queue, where it can be picked up by a truck and delivered to its final destination. Once train unloading is over, the crane resource is released back to the pool and the train is ready to pick up any pending cargo from a second storage queue. Train loading proceeds in a similar manner as before, that is, a crane is seized during train loading. After loading and unloading operations the train enters a queue. In case there is a train that is not required to drop or pick-up a load, it is also possible for it to directly enter the exit queue. In this situation, auxiliary variables and functions are used to monitor the conditions of trains that enter the railyard and to manage their movement. Movement between the railyard and the exit track is also modeled with the seize-release approach. The exit track is established as a resource to ensure that only one train exits at a time. A train can exit when trains are not coming in the opposite direction or when the next railway segment is double tracked. For some terminal agents, the actual process can be more complex because it may account for the operation of multiple train lines. For instance, trains from all lines eventually reach Northport, and there will be a workflow similar to that of **Figure 9.4** for every line. In other cases, trains approach a terminal from all directions, and follow different purposes. It is the case of Kauri, which has internal logic defined for three cases: trains passing through the terminal on its way to their final destination, trains with container imports that have arrived to their final destination, and trains picking up container exports to be transported to



including train speed, number of wagons per trains, number of cranes and forklifts at each terminal, and single or double tracking sections. For every experiment, the performance was monitored through resource utilization rates, number of sidings/tracks used at each terminal, and train timetables. The GUI displayed in Figure 9.6 allowed to monitor inventory levels at terminals, hence allowing to fine-tune model parameters and terminal resources. The experiments were not predefined, but rather defined on-the-go basis, meaning that the performance of the system was monitored during each setup, parameters and resources were adjusted to improve utilization rates, and to ensure that each train can perform a roundtrip within a period of one day and to guarantee balanced inventories at terminals. Parameters like loading and unloading times were assumed to be constant in order to avoid uncertainty and allow to make the experimental setups comparable. Orders were sourced from forests, factories and ports warehouses following a time-out rule.

### ***9.1.2. Costing***

Cost estimation was based on the parameters defined for every experiment. Accordingly, cost categories included: land, railyard sidings or tracks, handling equipment, double tracking sections, high speed section upgrade, rolling stock, detailed design and construction labor. Table 9.1 presents the unitary costs involved and the corresponding sources of information. Terminal areas were based on the number of loading units exchanged at each terminal. Table 9.2 presents reference values used for the estimation of terminal areas.

**Table 9.1:** Reference values for costing analysis

Assets	Cost (NZD)	Unit	Reference
Land	70	Squared metre	B. Wiegmans and Behdani (2018)
Tracks (on railyard)	1044	metre	B. Wiegmans and Behdani (2018)
Handling (Crane)	4,350,000	unit	B. Wiegmans and Behdani (2018)
Handling (Log loader)	200,000	unit	Marketbook (2020)
Diesel Locomotive	1,000,000	unit	WorldWide Rails (2020)
Rail wagon	60,800	unit	Made-in-China (2020)
High speed single track on existing stone rail road stone bed	1,619,750	kilometre	Compass International Inc. (2017)
Design and construction	14	% of subtotal	Compass International Inc. (2017)

**Table 9.2:** Reference values for terminal areas (B. W. Wiegmans, Masurel, & Nijkamp, 1999)

Type	Moves per year	Terminal Area (m2)
XXL Terminal	>500,000	400,000
XL Terminal	100,000-500,000	400,000
L Terminal	30,000-100,000	36,400
M Terminal	10,000-30,000	10,500
S Terminal	<10,000	9,000

## 9.2. Results and Discussion

There is a network of infrastructure and resources that supports the current operation of POA. Given a port relocation, it is likely that a new setup will be needed, and simulation experiments provide insights on the changes and interventions that would be required. Six simulation

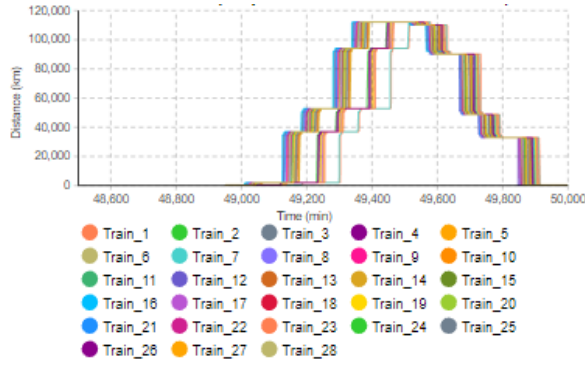
experiments were carried out to show different interventions on infrastructure capacity. Model time was set to 50,000 minutes (approximately 35 days) and on each experiment several parameters were tuned, including: train speed, number of forklifts, number of cranes, number of wagons per train, and segments with double tracking. Crane and forklift operation times were assumed to remain constant throughout all experiments, with values of 1.3 minutes and 1.5 minutes, respectively. Table 9.3 summarizes the setup and resource utilization used on each experiment. The overall aim was to evaluate trade-offs amongst parameters on each test and demonstrate how the model can be used to streamline the arrangement of a conceptual design. The first setup is based on a predefined number of resources at different terminals and on single-tracked sections throughout the network. During experiment two, the number of resources is reduced in order to improve utilization rates while maintaining smooth operations throughout the network. In this study, utilization is defined as the fraction of time that units were busy. There are terminals that, despite having reduced resources, still showed signs of resource underutilization; however, crane and forklift numbers were maintained throughout the remaining experiments as further reductions were non-feasible. In experiment three, double tracking is implemented in the sections comprehended between Wellsford and Waitakere. In this case, the major benefit of double tracking is the reduction of roundtrip travel times. **Figure 9.5** provides a representation for train timetables corresponding to line 1, which runs from Northport to Waitakere. Comparing Experiments 1 and 3, it is evident that double tracking cuts roundtrip times by approximately 500 minutes. In experiment 4, trains speeds are increased from 30 km/h to 50 km/h, leading to a further 500-minute reduction in roundtrip time. The reduction in travel time can be exploited because more trains could be added as needed. Moreover, additional time savings can enhance clearance for loading/unloading operations at terminals. The timetable for experiment 6 shows that the addition of 5 wagons per train slightly increases roundtrip times if compared to the timetables from Experiment 1. Still, in experiment

6 all trains managed to do a roundtrip before the end of the day shift, despite low train speeds (i.e. cruise speed) and single tracks throughout the network. During simulation, train speed actually varies within the network as the software accounts for train acceleration and deceleration within terminals. Table 9.3 shows that interventions associated with Experiments 2, 3 and 4 do not cause major impact on resource utilization. Experiments 5 and 6 are the exception; adding additional wagons reduces queues, hence requiring additional resource operation that leads to higher utilization rates in some cases. **Figure 9.6** contrasts queue levels for experiments 2, 3, 4 and 6. An accumulative trend of queue levels was observed during the execution of Experiment 2. In experiment 3, the implementation of double tracking partially improved the cumulative effect at some terminals. Still, long queues were showing signs of accumulation at Dargaville. The addition of extra wagons under Experiment 5, lead to a relief of log volumes from the terminal at Dargaville. Furthermore, additional wagon numbers allowed to reduce queues in other dairy handling ports leading to additional benefits that can potentially represent cost savings in regard to a reduction in storage space at terminals.

**Table 9.3:** Setup and terminal resource utilization for different simulation experiments

Description	Exp. 1	Exp. 2	Exp. 3	Exp. 4	Exp. 5	Exp. 6
Train speed (km/h)	35	35	35	50	35	35
Number of forklifts						
(Utilization %)						
Moerewa	5 (2.8%)	3 (4.5%)	3 (4.6%)	3 (4.7%)	3 (4.9%)	3 (4.7%)
Northport	10 (3.8%)	8 (4.7%)	8 (4.8%)	8 (4.8%)	8 (5.1%)	8 (5.0%)
Portland	10 (1.9%)	3 (4.6%)	3 (4.7%)	3 (4.4%)	3 (5.5%)	3 (5.3%)
Dargaville	5 (2.0%)	3 (3.3%)	3 (3.3%)	3 (3.3%)	3 (3.8%)	3 (3.7%)
Wellsford	5 (0.01%)	1 (0.03%)	1 (0.02%)	1 (0.05%)	1 (0.03%)	1 (0.08%)
Helensville	5 (1.6%)	4 (2.1%)	4 (2.1%)	4 (1.9%)	4 (1.9%)	4 (1.9%)
Number of Cranes						
(Utilization %)						
Moerewa	5 (1.9%)	3 (2.5%)	3 (2.5%)	3 (2.5%)	3 (2.3%)	3 (2.4%)
Kauri	5 (0.09%)	1 (0.4%)	1 (0.4%)	1 (0.6%)	1 (0.5%)	1 (0.5%)
Whangarei	5 (0.7%)	1 (3.6%)	1 (3.4%)	1 (3.4%)	1 (3.8%)	1 (3.8%)
Northport	10 (12.4%)	10 (13.0%)	10 (13.5%)	10 (13.4%)	10 (11.5%)	10 (10.5%)
Maungaturoto	5 (0.04%)	1 (0.1%)	1 (0.2%)	1 (0.2%)	1 (0.2%)	1 (0.1%)
Waitakere	10 (10.8%)	10 (11.3%)	10 (11.2%)	10 (11.1%)	10 (12.3%)	10 (12.3%)
Wagons per train	20	20	20	20	25	25
Double track segments	All single track	All single track	Wellsford-Waitakere	Wellsford-Waitakere	Wellsford-Waitakere	All single track
Total number of railyard tracks	90	91	85	101	84	89

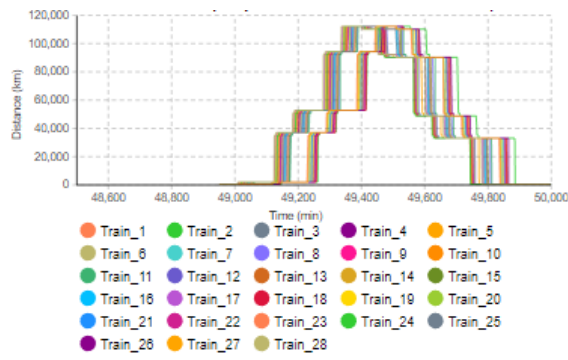




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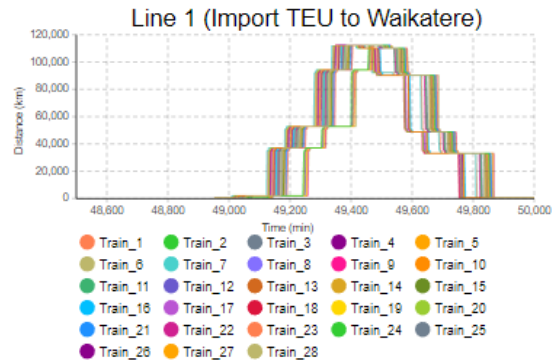
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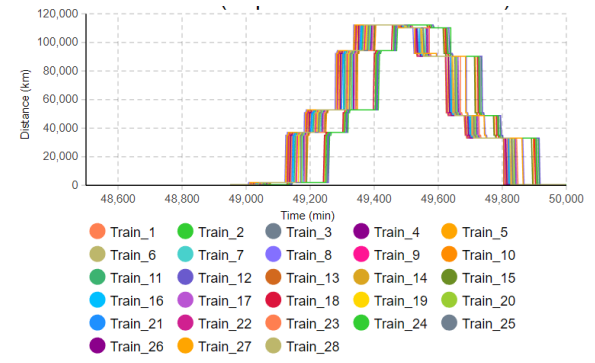
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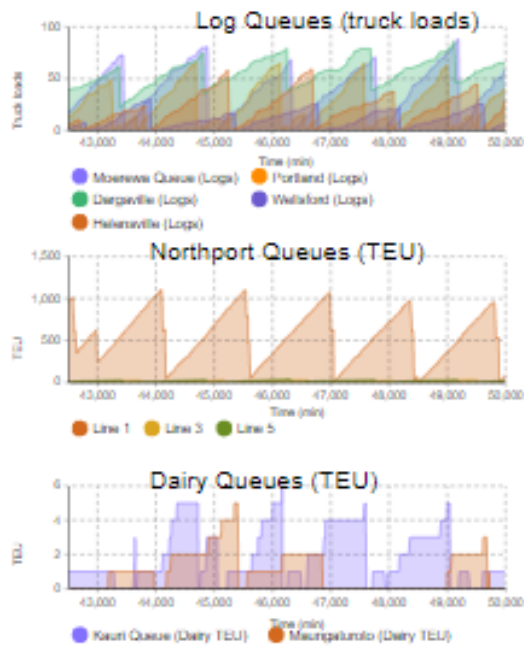


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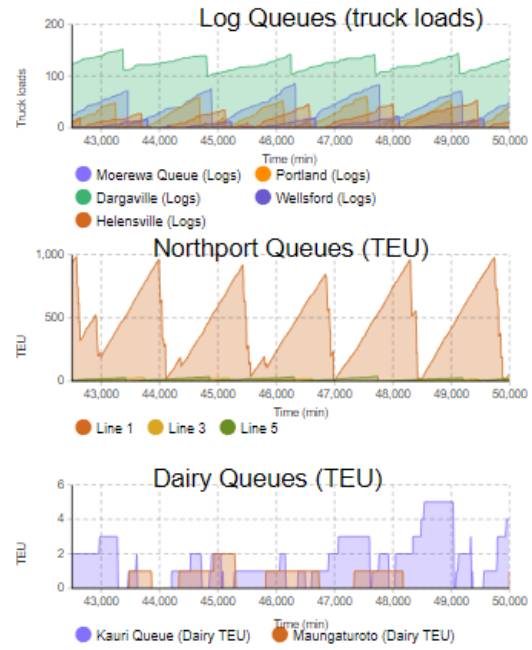


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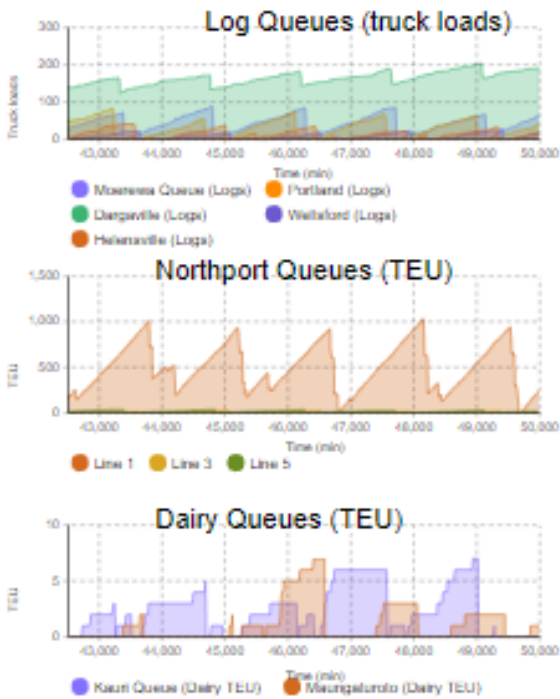
**Figure 9.5:** Timetables for different experiments: (a) Experiment 1; (b) Experiment 2; (c) Experiment 3; (d) Experiment 4; (e) Experiment 5; (f) Experiment 6



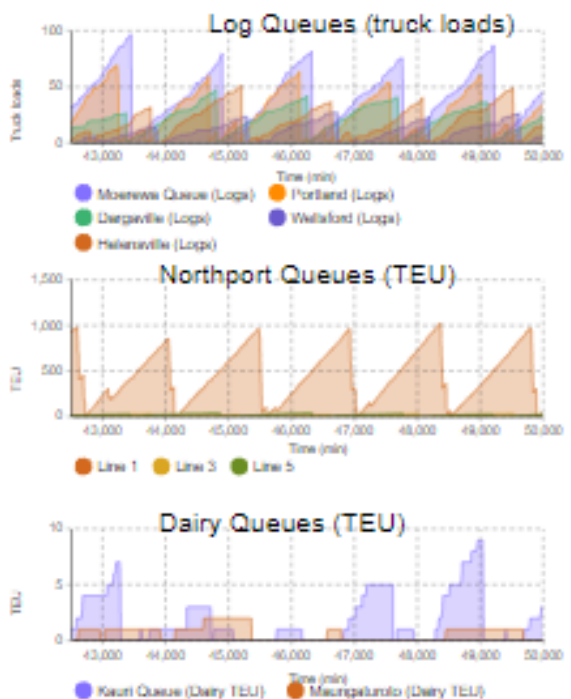
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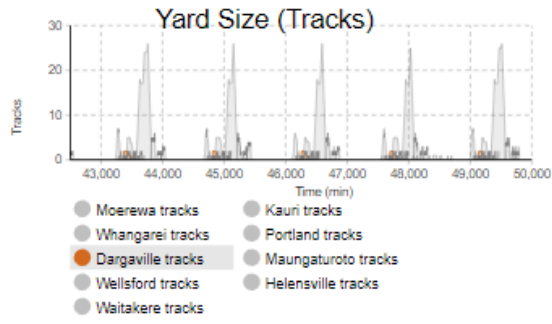


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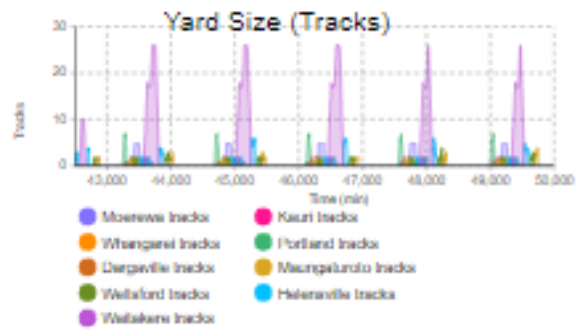
**Figure 9.6:** Queues at different terminals: (a) Experiment 2; (b) Experiment 3; (c) Experiment 4; (d) Experiment 6

Table 9.3 includes the total number of railyard tracks required for each experiment. Comparing number of tracks for Experiments 2 and 3 illustrates the benefit that double tracking has on railyard size: the number of tracks or sidings is reduced by 6. The increase in train speed affects railyard size as it shifts track numbers from 85 in Experiment 3, to 101 in Experiment 4. Figure 9.7 shows tracks used in railyards against model time. Figure 9.7 exposes how the upgrade in train speed (Experiment 4) results in additional track requirements from terminals throughout the network. In general, there are different trade-offs at stake, involving upgrades in rolling stock, railway network and terminal tracks. All experiments are based on the implementation of the Network analysis Component's best-case scenario, meaning that the performance in terms of energy consumption is assumed equal for all experiments because they involve the same transport and terminal operations.

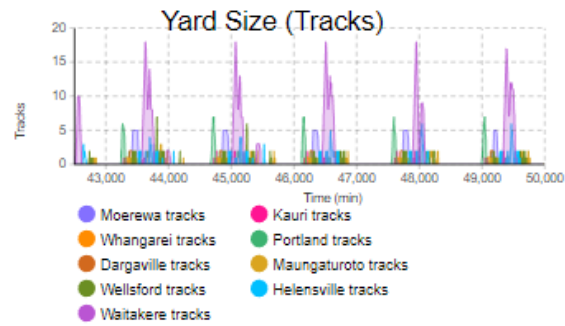
A cost analysis was needed in order to identify the most effective interventions. Figure 9.8 presents the results of the cost analysis. In the worst case (Experiment 4), the costs can reach a total of approximately 1.2 billion NZD, mainly owed to a major upgrade on the railway network that could allow the movement of faster trains. An investment of such magnitude could be considered if volumes from other commodities lead to the adoption of additional train services. An increment in train services could also be enhanced through double tracking specific sections. If double tracking was the desired pathway, the setup of Experiment 5 would be the most suitable option as it not only allows for a coordinated movement of daily train services but also manages to avoid the steady increase of inventory levels at terminals.



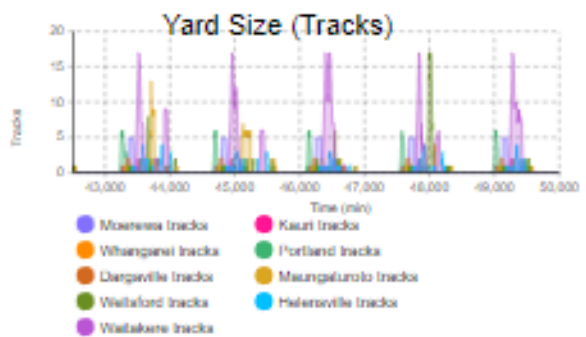
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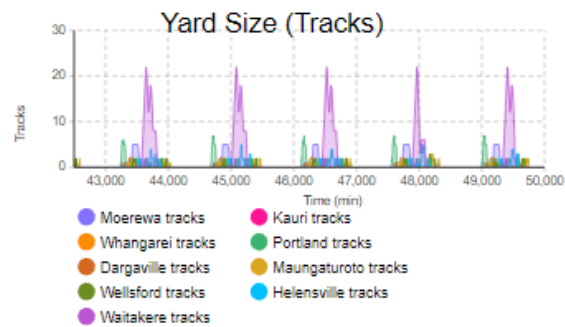
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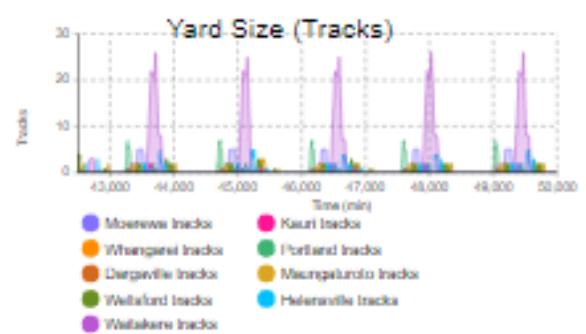
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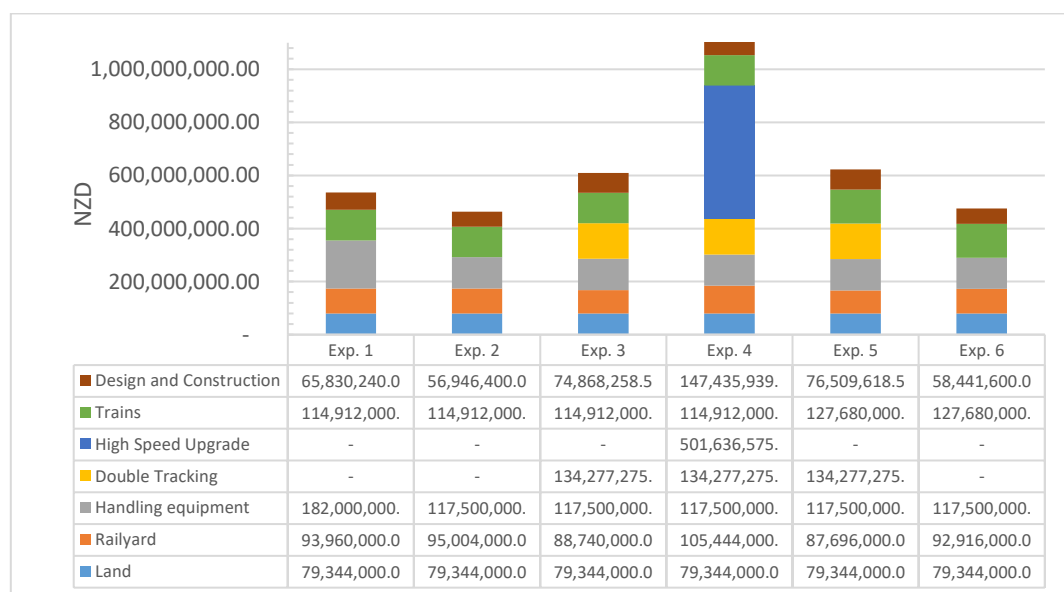
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(f)

**Figure 9.7:** Railyards size: (a) Experiment 1; (b) Experiment 2; (c) Experiment 3; (d) Experiment 4; (e) Experiment 5; (f) Experiment 6

The results suggest that Experiment 6, with a corresponding total cost of approximately 476 million NZD, would be the most cost-effective setup because it enhances a continuous operation of train services without the need of costly network upgrades and is associated with low-inventory levels at terminals. The analysis was based on the transport demand associated to three sectors, meaning that the movement of additional freight volumes would require the implementation of double tracking in order to allow the adoption of additional train services. However, one of the sectors considered is forestry, and according to past trends and recent projections, log volumes fluctuate over time. It is expected that within the next two decades, activity associated to log transportation will decrease. Despite the reduced number of handling resources at Kauri in the North and Maungaturoto and Wellsford in the South, the utilization rates were extremely low. A further set of simulation experiments could consider fewer terminals, where Moerewa could absorb the activity from Kauri and Maungaturoto and Wellsford could fuse at an intermediate location. The reduction of terminals would also need to be tested through simulation, as less terminals implies a reduction in land costs but also limits the frequency of train services in the network.



**Figure 9.8:** Cost assessment for interventions associated to different simulation experiments

### **9.3. Summary**

This chapter described the third component of STRATCODE, a GIS-based DES model. Component 3 is built upon the concept of structural and control elements used in previous studies. The originality of the model setup is its ability to connect network design, train scheduling, terminal and hauling operations while interrogating the capacity needed to enhance the analytical solution from the network analysis component. The simulation model was built with Anylogic software and contemplated train, truck, forest, factory, and terminal agents interacting within a GIS space in response to optimal shipping plans queried from a database. The model performance varied with changes to parameters related to terminal, railyard, and railway infrastructure assets. A conceptual design was constructed upon the execution of six simulation experiments that showed the most cost-effective parameters and network setup. The results suggest that the implementation of strategic terminals, with corresponding handling resources and railyards, should be prioritized over any upgrades on railway infrastructure.

## **Chapter 10: Conclusions**

This chapter presents section presenting a concluding discussion section, the main conclusions and areas for further research.

### **10.1. Discussion**

The development of the energy scenario modelling approach in Chapter 4 served to illustrate the idea that a policy study may not necessarily be linked to a complex transport demand model, and can be implemented given transport statistics on a broad scale. This represents a limitation and a risk because it is really easy to speculate on the adoption of unproven technologies, or unfounded shifts in modal share. This case was the exception, as the scenarios were founded on figures from the NFDS and also on estimates obtained through the execution of different modeling methodologies throughout the thesis. The model was executed for different scenarios resembling changes in modal share, reduction in transport activity, electrification of rail and a combination of different alternatives. The model was later adopted as an auxiliary component within STRATCODE in the form of an emissions calculator. The model was particularly useful as it is able to estimate direct and indirect GHG emissions.

The implementation of the input-output model in Chapter 5, allowed to understand some of the limitations of conventional transport demand modelling approaches. Despite its aggregated nature, the model demands a substantial amount of data and in some cases the absence of it leads to the adoption of several assumptions. The model relies on a set of fixed input-output coefficient tables for every region. Generally, these tables are available on a national scale, demanding the implementation of additional bi-proportional fitting procedures along with the

use of regional statistics. The fixed feature is a limiting factor, as it assumes that the productive structure within a region remains constant. A new generation of computable general equilibrium models addresses this issue and allows for the substitution of factors of production, although, the approach still relies on multiregional coefficient tables for model calibration. At the core of the RUBMRIO approach, there is a logistic function used for origin and mode allocation. The estimation of the logit function also relies on the availability of a commodity flow survey, which further limits the adoption of the model in terms of data availability.

RUBMRIO's inability to account for intermediate logistics is probably the most obvious limitation and is repeatedly mentioned in the literature. However, disaggregated approaches that embrace a logistics component are also limited by the availability of micro-data on individual behavioural preferences and patterns. This issue motivated the use of a preliminary freight distribution component, in combination with network planning and agent-based simulation.

The execution of the freight distribution component allowed to derive facility-to-facility pairs upon multiregional OD matrices. Depending on data availability for every sector, the freight distribution component combined different methodologies. The key contribution of the approach was the allocation of representative locations through the exercise of web scrapping functionality and sequential GIS processing tasks. This latter technique has the potential to be replicated on other agriculture-based sectors, as New Zealand counts on a robust open source land-cover database.

The GIS-based multimodal planning model was at the center of STRATCODE. The component had multiple purposes. Firstly, it allowed to further disaggregate OD pairs that after execution accounted for intermodal operations. The results from the disaggregation procedure lead to



generation of a database with optimal shipping plans for every OD pair. This database enhanced the connecting link between optimization and simulation. Component 2 also allowed to assess network traffic under different scenarios. The location of several intermodal terminals was also obtained upon the traffic assessment. Furthermore, traffic through every network edge allowed to estimate the number of services and trains to be tested during simulation. The contribution of the approach relied on the architecture of the model's algorithm which enhanced multifold functionality.

Different patterns of freight demand, network arrangements, and optimization criteria were implemented with the GIS-based intermodal planning model. The focus was concentrated on the implications of a full shift from POA to Northport. The results show that urban congestion will potentially be relieved. However, the results also suggest that the shift can conduct to an increase in energy demand, mainly because the distances between the new port location and warehouses in Auckland will be increased. Consequently, the adoption of a fully intermodal setup gains more relevance, as it can mitigate the impacts of longer travel distances on energy use and GHG emissions. Comparing time versus energy based optimization, reduction in energy savings and GHG emissions can be approximately 48% and 47%, respectively. The electrification of a congested railway segment can increase emissions reduction up to 54%. Yet, it is worth noting that the modal shift pathway remains as the alternative with the highest reduction potential. Further reductions could be achieved either through a reduction in transport activity (tkm) or through a relocation of factories and warehouses. The reduction in transport activity from the forestry sector appears as the most feasible option, as it is estimated that the production of wood logs will decrease within the next decade.

Simulation was complementarily utilized to interrogate the capacity of the best case scenario: a full shift to Northport, with a direct railway connection to Northport, and with shipments

following shortest paths based on energy use optimization. The overall aim of Component 3 was to enhance the analytic solution from Component 2 and setup simulation experiments that allowed to evaluate trade-offs amongst parameters to streamline the arrangement that delivers the best performance. Parameters included train speed, number of wagons per trains, number of cranes and forklifts at each terminal, and single or double tracking sections. For every experiment, the performance was assessed in terms of resource utilization rates, number of sidings/tracks used at each terminal, and train scheduling. Every experiment also delivered railyard sizes for all terminals considered in the study.

## **10.2. Main conclusions**

Mode and origin choices, with large utilities are associated to higher probabilities. Current decision-making behavior prioritizes cost, reliability and time attributes. The model in Chapter 5 only considered cost as an attribute, which itself depended on fossil fuel price. An escalation in fuel prices make railway mode a more appealing choice. However, the low cost associated to rail transportation, causes a dispersion in the pattern of flows, because in some cases it becomes cheaper to acquire inputs from remote locations through rail than from local sources through trucks. This phenomenon leads to a counterproductive rebound effect, which means that the expected energy savings from a modal shift were offset by an increased dispersion in freight flows. The application of the MRIO approach allowed to identify a limitation that has been overlooked in the literature, which is the propensity that utility maximizing approaches have for mimicking a rebound effect, hence limiting the applicability of these modelling approaches in long-term low-carbon transport planning.

New Zealand has counted with railway services for over 150 years. Despite the long history of rail in New Zealand, the share of TKMs has been decreasing and is currently bordering 10%, freight trains are still running at relatively low speeds, network infrastructure has been left on a degrading path as needed upgrades have been postponed or omitted. Despite its current condition, results from this thesis suggest that the current railway infrastructure can serve a much higher share of the freight task, given that effective accessibility to the network is provided. Simulation results were complemented with a costing assessment to identify the most cost-effective setup. The results suggest that costly interventions are not necessarily aligned with the most effective way forward. The setup associated to experiment 6 did not consider double tracking or a track upgrade to improve train speed, and can potentially foster a drastic reduction of emissions through the adoption of key intermodal terminals. Accordingly, future investments should prioritize the development of intermodal hubs that can improve supply chain accessibility to railway transportation, accessibility is the key. It is worth clarifying that other line items like traffic control systems, signals, crossing gates, storing equipment, and handling software were not included in the costing analysis. These items could be accounted for as part of the basic and detail design stages, where simulation can also take a protagonist role, especially for the design of terminals and ports.

STRATCODE can be conceived as a conceptual framework that can be applied to other contexts. In this thesis, the implementation of the framework includes methods that may be specific for New Zealand's case or even sector-specific. Although, the recommendation would be to maintain the aim and essence of the approach, which is to aid the process of building a long-term resilient concept of the freight transportation system, through the effective exploitation of benefits resulting from the combination of optimization and simulation. There are some elements that are and will be typical in other geographical contexts, particularly,

ongoing regional and international trade and the supporting infrastructure including road and railway networks, terminals and ports. All these elements have been characterized through the methodology presented in this thesis. STRATCODE embraces a whole systems approach and its embedded interconnection between optimization and simulation provides the versatility needed to connect network and terminal planning perspectives. The framework not only allows to engineer a future concept of the network layout but also interrogates the operational capacity needed to withstand a substantial modal shift to rail in response to carbon mitigation national strategies. These advantages are not only relevant in New Zealand and can potentially be used to assist the development of energy and transport policy in other countries and regions. It is worth noting that countries that currently lack railway infrastructure, can still adopt STRATCODE, as the framework can be used to distinguish freight corridors with significant traffic levels that can potentially be considered for the development of a railway network layout.

State-of-the-art agent-based freight models embrace a communication framework that supports negotiation and decision making amongst cognitive agents. STRATCODE accounts for the heterogeneity of actors in the supply chain, although the approach leaned towards a pure discrete event nature. There was no negotiation or cognitive behavior amongst agents, they only reacted to the presence of other agents, scheduled orders and events. The adoption of DES was relevant as the interaction of agents is not static, freight operations take place within a dynamic environment, where different events are simultaneously taking place at different layers of the system. Furthermore, recent models reported in the literature studied agent behaviour within a transportation market. In these models, agent behaviour has been calibrated upon surveys that reflect the status-quo which prioritizes cost and transit time over environmental considerations. Accordingly, STRATCODE deviates from these state-of-the-art

approaches, as agents are restricted to follow shipping plans that prioritize the use of railway, subsequently optimizing the use of energy resources.

### **10.3. Future Work**

The energy and environmental planning model in Chapter 4 has the ability to evaluate the impact of transport electrification in terms of GHG emissions and also in regard to power grid stability. The setup of the software allows to assign load and availability curves to different power consumption and generation technologies, respectively. One of the scenarios contemplated the electrification of a congested railway segment. The corresponding load curve assigned to this technology was assumed to be constant throughout the year. However, a flat electric load curve is very unlikely, so future studies could adopt load shapes based on the actual performance of electric freight trains in other regions. This consideration will result in more accurate estimates and could be of great value to power engineering studies. Moreover, a more profound study of the electrification pathway could support assessing the cost-effectiveness of the electrification pathway as pertinent costs would also include potential investments on energy storage, power generation and transmission.

The application of STRATCODE considered three sectors that are relevant to the country's economy. In general, the inclusion of other sectors would improve the accuracy of the capacity assessment, but is limited to the availability of sector-specific information. The National Freight Demand Study consolidates data from different sectors and has been a crucial resource in this study. However, more detailed applications of STRATCODE will likely depend on more robust sources. A good benchmark is the commodity flow survey from the US Department of Transportation. On the other hand, it seems that we are on the verge to exploit big data

applications on freight modelling. As logistics systems automate their operations and adopt technologies inspired on the internet of things, more data will be generated and ideally used by data-driven models that embrace the power of machine learning methods.

The geographic scope of the case study for the application of STRATCODE was focused on the North Part of the New Zealand's North Island, so coastal shipping was omitted from the assessment. This is a factor that should be handled carefully, specifically when it comes to the application of the simulation component. The addition of coastal shipping should not add a significant level of complexity as far as it concerns to the execution of Component 2. On the other hand, the workflows presented for the simulation counterpart only account for transshipment operations between trucks and trains. Adding coastal shipping would definitely require a reconfiguration of the logic behind the workflows, as resources would also need to serve yard and berth management. It will also require the use of additional shapefiles for the construction of coastal networks. Moreover, the increased level of complexity will lead to the need of additional computing resources. Nevertheless, all these modelling limitations are not limited by software technology, so they can be accounted in future updates of the framework.

The intermodal planning model could also broaden its scope by considering economic cost attributes and penalties depending on the type of commodity transported. This can be the case of perishable products that need to meet specific standards and timelines. Furthermore, the execution of shortest paths based on the minimization of economic costs could lead to the formulation of scenarios that better resemble a Business as Usual case, and hence allow delivering more realistic figures on energy use and travel time savings.

Component 2 allowed to select a subset of terminal locations from a collection of current KiwiRail stations. GIS-based multi-criteria decision analysis could be considered as a

complementary step to confirm the locations of intermodal terminals. This complementary step could be applied either before or after simulation. The latter case might be adequate, as it was observed that some terminals are associated to a minimal utilization of its resources, so potentially they can fusion with neighboring terminals. Multi-criteria decision analysis can also be used to deliver new locations for factories and warehousing, taking into account the pattern of flows and accessibility to ports and intermodal terminals.

The adoption of ABM is recurrently proposed as a technique that not only allows to study logistics activities but also enhance the interaction of different agents in the freight supply chain. Agent-based modelling capability to enhance communication and negotiation protocols amongst agents is definitely a very powerful tool. Several studies are taking advantage of this feature to evaluate the implementation of a universal web of logistics services, also known as the physical internet, allowing retailers and manufacturers to access open warehouses and distribution centers instead of dedicated facilities. The simulation model presented in this thesis contemplates the interaction of different agents from the freight system. The approach did not embrace negotiation amongst agents. There is potential to consider an additional cognitive agent that can track energy consumption within the system and prioritize the use of network resources on shipments with an *essential* nature. This would also require the conception of new metrics on essentiality, which have already been implemented on passenger transportation studies.

Simulation provides a digital representation of the dynamics of how a real system operates. This thesis was concerned with the representation of the freight system. The approach focused on network and operational resources. However, the realization of concepts that have been assessed through simulation, like the one presented in this thesis or other reported in the literature (i.e. physical internet, synchromodality), will likely rely on other technological

elements to enhance a regime of open data exchange between the actors of the freight supply chain. Potentially, tracking and sensing devices can provide routing data, real time conditions for shipments, traffic, and inventories. Managing this myriad of data resources, while overcoming technical and legal challenges represents an active area of research that is still at an early stage of development. Besides the technological challenges, digitalization also implies a progressive update in digital skills as we move away from analog technologies.



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## Appendix A: Code for RUBMRIO implementation

Chapter 3 presents the details of the algorithm behind a Random Utility Based Multiregional Input Output Model. This appendix presents the model implementation in Python, using a two sectors, two regions numerical example.

```
Import libraries
[1]: import numpy as np
import pandas as pd
import matplotlib.pyplot as plt

Declare auxiliary variables for number of regions (r) and sectors (s)
[2]: s=2
r=2

Define 2x2 arrays for technical coefficients in regions 1 and 2.
[3]: a_mn_1=np.array([[0.2,0.8],[0.7,0.4]])
a_mn_2=np.array([[0.2,0.8],[0.7,0.4]])
a_j_mn=list([a_mn_1,a_mn_2])

Set final demands for all sectors m and regions i
[4]: Y_m_i=np.array([[100,200],[20,50]])

Set transportation costs between regions for different sectors
[5]: d_n_ij=list([np.array([[2,10],[10,1]]),np.array([[2,10],[10,1]])])

Set dispersion factors for every sector
[6]: lambda_n=np.array([15,0.2])

Initialize purchase prices at region of origin for sectors n
[7]: b_n_j=np.array([[0,0],[0,0]],dtype=float)

Initialize trade flows between regions ij for every sector n
[8]: x_n_ij=list([np.array([[0,0],[0,0]],dtype=float),np.array([[0,0],[0,0]],
dtype=float)])

Initialize purchase costs for sectors n and regions j
```

```
[9]: c_n_j=np.array([[0,0],[0,0]],dtype=float)
```

Initialize utilities, production, consumption and trade coefficients

```
[14]: u_n_ij=list()
      t_n_ij=list()
      for t in range(s):
          u_n_ij.append(np.zeros((r,r),float))
          t_n_ij.append(np.zeros((r,r),float))
      X_n_i=np.zeros((s,r),dtype=float)
      C_n_j=np.zeros((s,r),dtype=float)
```

Create dataframe to record results of each iteration. Initialize iteration counter cc.

```
[12]: results = pd.DataFrame()
      cc=0
```

This chunk of code is part of a loop, meaning that it is solved for cc=200 iterations.

```
[16]: while cc<=200:
      # First Step. Calculation of utilities
      # First loop is based on number of sectors
      # Second and third loops based on number of regions
          for t in range(s):
              for i in range(r):
                  for j in range(r):
                      u_n_ij[t][i,j]=(-1)*(b_n_j[t,i]+d_n_ij[t][i,j])
      # Second step. Calculation of production
          for t in range(s):
              X_n_i[t]=np.sum(x_n_ij[t],axis=1)
      # Third step. Calculation of consumption
          for t in range(s):
              for i in range(r):
                  C_n_j[t,i]=np.sum(a_j_mn[i][t]*X_n_i[:,i])+Y_m_i[t,i]
      # Fourth step (a). Calculation of trade coefficients based on random utility
      k=0
          for t in range(s):
              for i in range(r):
                  s_exp=np.sum(np.exp(lambda_n[t]*u_n_ij[t][:,i]))
                  for j in range(r):
                      t_n_ij[t][j,i]=np.exp(lambda_n[t]*u_n_ij[t][j,i])/s_exp
      # Fourth step (b). Calculation of trade flows
          x_n_ij[t][j,i]=C_n_j[t,i]*t_n_ij[t][j,i]
          results.loc[cc,k] = x_n_ij[t][j,i]
          k=k+1
      # Fifth step. Calculation of costs
          for t in range(s):
              for i in range(r):
```

```

        c_n_j[t,i]=np.sum(x_n_ij[t][:,i]*(b_n_j[t]+d_n_ij[t][:,i]))/np.
->sum(x_n_ij[t][:,i])
    # Sixth step. Calculation of prices
    for t in range(s):
        for i in range(r):
            b_n_j[t,i]=np.sum(a_j_mn[i][:,t]*c_n_j[:,i])
    # Convergence Test
    cc=cc+i

```

Formatting of dataframe. An extra column is added to reference iteration numbers. Column names are given. For instance, sir12 reads flows between regions one and 2 for commodities for sector 1.

```

[17]: # Add additional column for number of iteration or run
results['Run'] = range(1, len(results) + 1)
#
results = results.add_prefix('X_')
results.rename(columns={'X_0': 'sir11',
                        'X_1': 'sir21',
                        'X_2': 'sir12',
                        'X_3': 'sir22',
                        'X_4': 's2r11',
                        'X_5': 's2r21',
                        'X_6': 's2r12',
                        'X_7': 's2r22',
                        'X_Run': 'Run'},
               inplace=True)

```

Convergence plot.

```

[18]: ## make convergence plot
ax = plt.gca()
results.plot(kind='line', x='Run', y='sir11', color='b', ax=ax)
results.plot(kind='line', x='Run', y='sir21', color='g', ax=ax)
results.plot(kind='line', x='Run', y='sir12', color='r', ax=ax)
results.plot(kind='line', x='Run', y='sir22', color='c', ax=ax)
results.plot(kind='line', x='Run', y='s2r11', color='m', ax=ax)
results.plot(kind='line', x='Run', y='s2r21', color='y', ax=ax)
results.plot(kind='line', x='Run', y='s2r12', color='k', ax=ax)
results.plot(kind='line', x='Run', y='s2r22', color='tab:pink', ax=ax)
ax.set(ylim=[0,2500], ylabel = 'Flow')
ax.legend(loc='upper center', bbox_to_anchor=(0.5, 1.05),
         ncol=3, fancybox=True, shadow=True)
plt.show()

```

## Appendix B: Code for linear optimization model

Chapter 5 presents a freight distribution model that integrates different methods. This appendix presents the implementation of the linear optimization problem in Python, using feature classes associated to the transportation to dairy products from factories to ports.

Import libraries. Arcpy functionality is used to query, manage and update GIS databases and feature classes. Pulp functionality is used to formulate and solve linear optimization problems. Pandas functionality allows to create and modify dataframes. Csv is used to read and write csv files. Os is used to set the working directory.

```
In [1]: from pulp import *
import pandas as pd
import arcpy as ap
import csv
import os
```

Set working directory

```
In [2]: os.chdir('C:\\Scenario Based Anylogic Simulation\\Dairy gravity documents')
```

Read file containing freight flows from gravity estimation (interregional flows). The file is used to build the region\_flow dataframe.


```
In [3]: region_flow = pd.read_csv('reg_flow_dairy.csv', sep=',', index_col = 'Region')
```

Set a workspace environment, so that arcpy commands have a reference of the database containing the GIS features to be used by the model.

```
In [4]: ap.env.workspace = "C:\\Scenario Based Anylogic Simulation\\Dairy gravity documents\\Dairy_files.gdb"
ap.env.overwriteOutput = "TRUE"
```

Assign names to the string file locations of factory, ports, and OD arcs features. The OD\_class address refers to the location of a line feature class that contains all possible OD combinations between factories and ports.

```
In [5]: factory_class = "C:\\Scenario Based Anylogic Simulation\\Dairy gravity documents\\Dairy_files.gdb\\dai
port_class = "C:\\Scenario Based Anylogic Simulation\\Dairy gravity documents\\Dairy_files.gdb\\NZ_por
OD_class = "C:\\Scenario Based Anylogic Simulation\\Dairy gravity documents\\Dairy_files.gdb\\factory_
```

<  >

We create a dictionary to record the solutions associated to each interregional OD pair.

```
In [ ]: solution = {}
```

This chunk of code is part of a for loop. During each iteration, variables are read from the feature classes and are further assigned as variables for the linear optimization problem.

```
In [6]: for k in region_flow.index:
# Create an empty list for nodes involved in the optimization problem
# corresponding to this iteration
Nodes = []
# Create an empty dictionary to store the [supply,demand] associated
# to each node
nodeData = {}
# Start assigning values corresponding to factory nodes
# Create variable to keep track of nodes that are of factory type
N_factories=0
# First part looks at production from factories (data extracted
# from feature class). The attributes extracted from this
# feature class are the region, id and share (based on factory
# annual capacity). In this case the variables assigned correspond
# to supply requirements extracted from the region_flow data frame.
# In this case a cursor is used to iterate over every feature and
# filter those that correspond to the k region involved in each
# iteration
with ap.da.UpdateCursor(factory_class,["Region", "LP_ID", "Region_share"])
as cur:
    for i,row in enumerate(cur,1):
        if(row[0] == k):
            Nodes.append(str(row[1]))
            N_factories = N_factories + 1
            nodeData[row[1]] = [(region_flow.sum(1)[k])*
                                (row[2]),0]
# Create a variable to keep track of nodes that are of port type
N_ports=0
# Second part looks at how many port are on every serviced region
# Demand is extracted given region flows and ports per region
# In this case only the region attribute is extracted, as there is
# on port per region and the ID's correspond to region names
for j in region_flow.columns:
# Iteration discriminates cells with zero flows
    if(region_flow.loc[k,j] > 0):
        counter = 0
        with ap.da.UpdateCursor(port_class,["Region"]) as cur:
            for i,row in enumerate(cur,1):
                if(row[0] == j):
                    Nodes.append(str(row[0]))
                    N_ports = N_ports + 1
                    nodeData[row[0]] = [0, region_flow.loc[k,j]]
    else:
        continue

## Create arcs involved in the iteration using a nested
## loop

Arcs = []
for i in range(N_factories):
    for j in range(N_factories, N_factories + N_ports):
        Arcs.append((Nodes[i],Nodes[j]))
```

```

Arcs = []
for i in range(N_factories):
    for j in range(N_factories, N_factories + N_ports):
        Arcs.append((Nodes[i],Nodes[j]))

## Initialize dictionary of arcData
arcData = {}
for i in Arcs:
    arcData[i] = [0,0,0]
## Use cursor again to iterate over OD matrix and get routed distances
## Get data from OD matrix. There is a split operation in order
## to extract the IDs of the nodes forming each arc.
with ap.da.UpdateCursor(OD_class,["Name", "Total_Length"]) as cur:
    for i,row in enumerate(cur,1):
        i_index = row[0].split(' - ')
        if(i_index[0] in Nodes and i_index[1] in Nodes):
            arcData[(i_index[0], i_index[1])] = [round(row[1],1),0,nodeData[i_index[0]]
            cur.updateRow(row)

# Splits the dictionaries to be more understandable
(supply, demand) = splitDict(nodeData)
(costs, mins, maxs) = splitDict(arcData)

# Creates the boundless Variables
vars = LpVariable.dicts("",Arcs,0,max(region_flow.max())*1000,
                        cat='Continuous')

# Creates the upper and lower bounds on the variables
for a in Arcs:
    vars[a].bounds(mins[a], maxs[a])

# Creates the 'prob' variable to contain the problem data
prob = LpProblem("Flow Allocation per Regions",LpMinimize)

# Creates the objective function
prob += lpSum([vars[a]* costs[a] for a in Arcs]), "Total Cost of Transport"

# Creates all problem constraints - this ensures the amount going into each
# node is at least equal to the amount leaving
for n in Nodes:
    prob += (supply[n]+ lpSum([vars[(i,j)] for (i,j) in Arcs if j == n]) >=
            demand[n]+ lpSum([vars[(i,j)] for (i,j) in Arcs if i == n])),
            "Dairy Flow Conservation in Node %s"%n

# The problem data is written to an .lp file
prob.writeLP("LogAllocation.lp")

# The problem is solved using PuLP's choice of Solver.
# Every iteration corresponds to a different optimization
# problem. Each solution is stored in a dictionary (solution)
prob.solve()
for v in prob.variables():
    aux = v.name.split("")
    solution[aux[1] + " - " + aux[3]] = v.varValue

```

Finally a new field is added to the OD feature class. Then, the corresponding flow is assigned using a cursor and the values from the solution dictionary

```

In [7]: ap.AddField_management("factory_port_OD", "Flow", "DOUBLE")
with ap.da.UpdateCursor(OD_class,["Name", "Flow"]) as cur:
    for i,row in enumerate(cur,1):
        if(row[0] in solution.keys()):
            row[1] = solution[row[0]]
            cur.updateRow(row)

```

## Appendix C: Code for iterative proportional fitting model

Chapter 5 presents a freight distribution model that integrates different methods. This appendix presents the implementation of an iterative proportional fitting model in Python, using regional flows reported in the NFDS and annuals exports for the dairy sector.

Import libraries. Ipfm functionality is used to perform bi-proportional iterative proportional fitting. Pandas functionality allows to create and modify dataframes. Os allows to set working directory. Numpy is used to perform operations with vector data.

```
In [1]: from ipfm import ipfm
import pandas as pd
import os
import numpy as np
```

Set working directory and read csv file containing dairy flows reported in NFDS

```
In [2]: os.chdir('C:\\Scenario Based Anylogic Simulation\\Dairy gravity documents')
region_flow = pd.read_csv('dairy_flows.csv', sep=',', index_col = 'Region')
```

Read csv files containing OD cost matrix (average distance between depots and ports) into a dataframe

```
In [3]: distance = pd.read_csv('C:\\Scenario Based Anylogic Simulation\\Dairy gravity documents\\avg_distance_
< >
```

Get row and column totals from flows dat frame. Convert units from million tonnes to tonnes.

```
In [4]: region_flow['Total'] = region_flow.sum(1)
region_flow.loc['Total',:] = region_flow.sum()
region_flow = 1000000*region_flow
```

Create a list of region names

```
In [5]: Regions = ['Northland', 'Auckland', 'Waikato', 'Bay_of_Plenty',
'Hawkes_Bay', 'Taranaki', 'Manawatu', 'Wellington']
```

Create a data frame with totals (incoming and outgoing) by region. Columns refer to actual values and target values.

```
In [6]: totals = pd.DataFrame(np.zeros(shape=(8,4)), columns = ['I_Production', 'I_Consumption', 'F_Production',
index = Regions)
totals['I_Production'] = region_flow.loc[:, 'Northland': 'Wellington'].sum(1)
totals['I_Consumption'] = region_flow.loc['Northland': 'Wellington',:].sum()
< >
```

Normalize totals to match tonnes of annual dairy exports

```
In [7]: o_factor = 1662700/totals['I_Production'].sum()
d_factor = 1662700/totals['I_Consumption'].sum()
totals['F_Production'] = o_factor*totals['I_Production']
totals['F_Consumption'] = d_factor*totals['I_Consumption']
```

Create a data frame in a form compatible with ipfn librarie's format. Set two "for" loops to fill the dataframe with current values from the regional flow data frame.

```
In [8]: NI_ipf_df = pd.DataFrame(columns = ['Origin', 'Destination', 'total'])
for i in Regions:
    for j in Regions:
        NI_ipf_df = NI_ipf_df.append(pd.DataFrame([[i, j, region_flow.loc[i,j]]],
                                                    columns = ['Origin', 'Destination',
                                                                'total'])))
```

Get target aggregates for model estimation.

```
In [9]: xi_NI = NI_ipf_df.groupby('Origin')['total'].sum()
xj_NI = NI_ipf_df.groupby('Destination')['total'].sum()
for i in Regions:
    xi_NI.loc[i] = totals.loc[i,'F_Production']
    xj_NI.loc[i] = totals.loc[i,'F_Consumption']
aggregates_NI = [xi_NI, xj_NI]
```

Only two dimensions are considered in the fitting process, however the software can perform fitting based on more dimensions. The fitting function is called, using arguments for current flows, target totals and the specific dimensions. Then another function is called to predict flows that match the new target totals.

```
In [14]: dimensions = [['Origin'], ['Destination']]
IPF_NI = ipfn(NI_ipf_df, aggregates_NI, dimensions)
pred_NI_ipf_df = IPF_NI.iteration()
pred_NI_ipf_df['total'] = pred_NI_ipf_df['total'].astype(int)
```

The predicted values are arranged into a dataframe that will be later used to carry out the calibration of a gravity model. The new dataframe has a format compatible with the library that has functionality for spatial interaction model calibration.

```
In [12]: NI_grav_df = pd.DataFrame(columns = ['Origin', 'Destination', 'Flow(tonnes)', 'O_totals', 'D_totals',
                                                'Distance(km)'])
for i in region_flow.index:
    for j in region_flow.index:
        NI_grav_df = NI_grav_df.append(
            pd.DataFrame([[i, j, pred_NI_ipf_df.loc[(pred_NI_ipf_df['Origin'] == i)
                                                    & (pred_NI_ipf_df['Destination'] == j),
                                                    ['total']].values[0][0],
                        totals.loc[i,'F_Production'], totals.loc[j,'F_Consumption'],
                        distance.loc[i,j]/1000]], columns = ['Origin', 'Destination',
                                                            'Flow(tonnes)', 'O_totals',
                                                            'D_totals', 'Distance(km)'])))
```



## Appendix D: Code for calibration of gravity models

Chapter 5 presents a freight distribution model that integrates different methods. This appendix presents the calibration of two forms of gravity models in Python, using regional flows reported in the NFDS and annuals exports for the dairy sector.

Import libraries. OS is used to set working directory. Pandas is used to create and manipulate data frames. Math is used to perform mathematical operations. The production and gravity libraries are imported from the pysal package. They are used to calibrate production-constrained and unconstrained gravity models.

```
In [1]: import os
import pandas as pd
from pysal.model.spint.gravity import Production
from pysal.model.spint.gravity import Gravity
import math
```

Set working directory

```
In [2]: os.chdir('C:\\Scenario Based Anylogic Simulation\\Container Gravity Documents')
```

Read population numbers by regions

```
In [3]: population = pd.read_csv('region_population.csv', index_col='Region')
```

Read dataframe created upon the execution of iterative proportional fitting procedure.

```
In [4]: NI_grav_df = pd.read_csv('NI_grav_df.csv')
NI_grav_df = NI_grav_df.astype({'Flow(tonnes)': int, 'O_totals': int, 'D_totals': int})
```

Add columns for employment counts at destination region and assign corresponding values

```
In [5]: NI_grav_df['pop_region']=0
for i, row in NI_grav_df.iterrows():
    NI_grav_df.loc[i, 'pop_region'] = population.loc[row['Origin'], 'Value']
```

North Island gravity models estimation, two families considered. Production-constrained fixes production values and sets population numbers for destination variables. Distance in kilometres is assigned as an attribute considered for an impedance function.

```
In [6]: flows_NI = NI_grav_df['Flow(tonnes)'].values
Oi_NI = NI_grav_df['O_totals'].values
Dj_NI = NI_grav_df['pop_region'].values
Dij_NI = NI_grav_df['Distance(km)'].values
Origin_NI = NI_grav_df['Origin'].values
Destination_NI = NI_grav_df['Destination'].values
```

Models are calibrated and new interregional OD flows are predicted.

```
In [7]: gravity_NI = Gravity(flows_NI, Oi_NI, Dj_NI, Dij_NI, 'exp')
production_NI = Production(flows_NI, Origin_NI, Dj_NI, Dij_NI, 'exp')
NI_grav_df['Grav_Fit'] = gravity_NI.yhat
NI_grav_df['PC_Grav_Fit'] = production_NI.yhat
```

Get indicators of regression fit including: Coefficients of determinations, standardized root mean square error and Akaike information criterion

```
In [8]: print('R square of NI production constrained gravity model:')
print(production_NI.pseudoR2)
print('R square of NI unconstrained gravity model:')
print(gravity_NI.pseudoR2)
print('SRMSE of NI production constrained gravity model:')
print(production_NI.SRMSE)
print('SRMSE of NI unconstrained gravity model:')
print(gravity_NI.SRMSE)
print('AIC of NI production constrained gravity model:')
print(production_NI.AIC)
print('AIC of NI unconstrained gravity model:')
print(gravity_NI.AIC)
```

## Appendix E: Code for GIS-based transport planning model

Chapter 6 introduces an algorithm for a GIS-based intermodal transportation planning model. This appendix presents the algorithm's implementation in Python, using facility to facility flows derived upon the execution of a freight distribution component. The script uses a network dataset, GIS point and line features created through ArcGIS.

Import libraries. Arcpy functionality is used to query, manage and update GIS databases and feature classes. Moreover, this script uses functionality from the network analyst component to access network datasets, set up route analysis and run shortest path optimizations. Sys allows to build a try except structure to execute code while no exception are raised.

```
In [1]: import arcpy as ap
import sys
```

Set environment and enhance network analyst.

```
In [2]: ## set environment
ap.env.workspace = "C:\\Patricio\\Future Energies Paper\\Geographic Data"
ap.env.overwriteOutput = "TRUE"
ap.CheckOutExtension("Network")
```

Assign names to the string file locations of origins, destinations, od pairs features. The OD\_class address refers to the location of a line feature class that contains arcs representing flows from origins to destinations.

```
In [3]: ## Set names for files with points and arcs (flows)
flow_feature = "C:\\Patricio\\Future Energies Paper\\Geographic Data\\NZ_model_features_upgrade.gdb\\NI_Port_Warehouse_OD_Correc
origins = "C:\\Patricio\\Future Energies Paper\\Geographic Data\\NZ_model_features_upgrade.gdb\\NZ_Ports_Corrected_UTMprojected"
destinations = "C:\\Patricio\\Future Energies Paper\\Geographic Data\\NZ_model_features_upgrade.gdb\\Warehouse_Corrected"
```

Set geodatabase name and path to its location. Build new geodatabases associated to the specific commodity considered in the assessment.

```
In [4]: # Set Local variables
out_gdb_path = "C:\\Patricio\\Future Energies Paper\\Geographic Data"
# Set name of geodatabase based on type of flows, this name is also used to define field name for
# fields in road_analysis, rail_analysis and transshipment_analysis.
out_gdb_name = "Port_Warehouse_shift_link"
# Create geodatabase for specific type of flow
ap.CreateFileGDB_management(out_gdb_path, out_gdb_name)
out_path = out_gdb_path + "\\\" + out_gdb_name + ".gdb"
```

Create a feature class to gather all origin and destination points participating in the analysis. The spatial reference is set to be equal to the one from the flows feature, Coordinate System: GCS\_NZGD\_2000 and a transverse mercator projection. An additional field is added for the identification string.

```
In [5]: out_name = "stops"
geometry_type = "POINT"
# Execute CreateFeatureclass
ap.CreateFeatureclass_management(out_path, out_name, geometry_type, spatial_reference = flow_feature)
# Create field for LP_ID
ap.AddField_management(out_path + "\\\" + out_name, "LP_ID", "TEXT")
# Assign variable to stops feature
stops = out_path + "\\\" + out_name
```

A feature dataset (collection of feature classes) is created for edges and routes to be delivered by the execution of shortest path routes. The paths variables (file locations) are provided.

```
In [6]: # Create feature dataset for "routes"
ap.CreateFeatureDataset_management(out_path, "routes", origins)
routes_path = out_path + "\\\" + "routes"
# Create feature dataset for "edges"
ap.CreateFeatureDataset_management(out_path, "edges", origins)
edges_path = out_path + "\\\" + "edges"
```

A cursor is used to query information from the origins feature and insert rows on stops feature. Id's are assigned. "SHAPE@XY" allows to set the coordinate of each point in the feature class.

```
In [7]: with ap.da.SearchCursor(origins, ["Region", "SHAPE@XY"]) as cur_a:
        for i, row in enumerate(cur_a, 1):
            cur_b = ap.da.InsertCursor(stops, ["LP_ID", "SHAPE@XY"])
            cur_b.insertRow([row[0], row[1]])
```

Similarly, a cursor is used to query information from the destinations feature and insert rows on stops feature.

```
In [8]: with ap.da.SearchCursor(destinations, ["LP_ID", "SHAPE@XY"]) as cur_a:
        for i, row in enumerate(cur_a, 1):
            cur_b = ap.da.InsertCursor(stops, ["LP_ID", "SHAPE@XY"])
            cur_b.insertRow([row[0], row[1]])
```

Specify path for the location of the network dataset to be used during network analysis. The paths for the location of three additional features are provided. The accumulated network traffic will be assigned to every edge of the road, rail and transshipment features. A "intermodal\_data" dictionary is created to store information on the optimal solution paths for every shipment. The length, time and energy associated to each path will depend on the criteria used for optimization.

```
In [9]: inNetworkDataset = "C:\\Patricio\\Future Energies Paper\\Geographic Data\\BAU_shift_link.gdb\\intermodal_upgrade\\intermodal_upg
road = "C:\\Patricio\\Future Energies Paper\\Geographic Data\\BAU_shift_link.gdb\\intermodal_upgrade\\road_analysis"
rail = "C:\\Patricio\\Future Energies Paper\\Geographic Data\\BAU_shift_link.gdb\\intermodal_upgrade\\rail_analysis"
transshipment = "C:\\Patricio\\Future Energies Paper\\Geographic Data\\BAU_shift_link.gdb\\intermodal_upgrade\\transshipment_analy
intermodal_data = {}
```

Add reference fields to record intermediate stops: access station ID, exit station ID, and mode (truck, train) assigned on every leg

```
In [14]: ap.AddField_management(flow_feature, "MODE", "TEXT")
ap.AddField_management(flow_feature, "ACCESS", "TEXT")
ap.AddField_management(flow_feature, "EXIT", "TEXT")
```

Iterations begin. A cursor is used to navigate through each OD pair from the flow feature class. The exploration is guided by the use of origin and destination ids.

```
In [12]: with ap.da.UpdateCursor(flow_feature, ["O_ID", "D_ID", "Flow_tonnes", "MODE", "ACCESS", "EXIT"]) as cur:
        for i, row in enumerate(cur, 1):
            # Select origins and destinations for stops input. Condition only North Island stops
            try:
                # Create Layer for points selection
                ap.MakeFeatureLayer_management(stops, "stops_lyr")
                # Select temporal (updated on each iteration) points based on ID attributes
                where_clause_1 = "LP_ID" + " = " + str(row[0]) + ""
                temp_select = ap.SelectLayerByAttribute_management('stops_lyr', 'NEW_SELECTION', where_clause_1)
                where_clause_2 = "LP_ID" + " = " + str(row[1]) + ""
                ap.SelectLayerByAttribute_management('stops_lyr', 'ADD_TO_SELECTION', where_clause_2)
                # Build a temporal Layer, and assign name based on the ids of the origin destination points involved
                # In this case energy is set for the optimization criteria
                inStops = temp_select
                route_name = str(row[0]) + "_" + str(row[1])
                result_object = ap.na.MakeRouteLayer(inNetworkDataset, route_name, "Energy")
                # Get the network analysis class names from the route Layer
                layer_object = result_object.getOutput(0)
                sublayer_names = ap.na.GetNAClassNames(layer_object)
                stops_layer_name = sublayer_names["Stops"]
                routes_layer_name = sublayer_names["Routes"]
                # Load stops to be used during route analysis and also define the names of the features
                # that integrate the network dataset
                ap.na.AddLocations(layer_object, stops_layer_name, inStops, search_criteria =
                    [{"nyards_rail", "NONE"}, {"nyards_road", "SHAPE"}, {"nyards_transshipment", "NONE"},
                     {"nyards_stations_road", "SHAPE"}, {"nyards_stations_train", "SHAPE"},
                     {"intermodal_upgrade_railyards_NO_Junctions", "NONE"}])
                # Solve the route Layer
                ap.na.Solve(layer_object)
                # Get routes sublayer and export it to feature
                routes_sublayer = ap.mapping.ListLayers(layer_object, routes_layer_name)[0]
                # Record the resulting route as a new feature class
                ap.management.CopyFeatures(routes_sublayer, routes_path + route_name)
```

```

ap.management.CopyFeatures(routes_sublayer, routes_path + route_name)
# Get information of the edges that integrate the solution
ap.na.CopyTraversedSourceFeatures(layer_object, edges_path, "TraversedEdges_" + route_name,
    "TraversedJunctions_" + route_name, "TraversedTurns_" + route_name)
temp_junction = edges_path + "\\ " + "TraversedEdges_" + route_name
# Every element of the dictionary is a list containing information of a shortest path,
# associated to a specific OD pair
intermodal_data[route_name] = []
# Need to determine if the transshipment points are either to access or exit the railway network
# In case there are not any transshipment points, need to know if shipment was only truck or only rail
# This part uses a cursor to navigate through the edges involved in the solution
# and determine the stops and modes assigned to every Leg. Furthermore, the corresponding
# flow is assigned to each edge of the solution
with ap.da.SearchCursor(temp_junction, ["SourceName", "SourceOID", "Attr_Energy"]) as cur_b:
    for j, row_b in enumerate(cur_b, 1):
        if (j==1):
            ACCESS = row_b[0]
            if(row_b[0] == "nyards_transshipment"):
                intermodal_data[route_name].append(row_b[1])
                with ap.da.UpdateCursor(transshipment, ["OBJECTID", "Railyards_Port_Warehouse", "Energy"]) as cur_c:
                    for row_c in cur_c:
                        if(str(row_b[1]) == str(row_c[0])):
                            row_c[1] += row_b[2]
                            row_c[2] += row_b[2]*row_b[2]
                            cur_c.updateRow(row_c)
            elif(row_b[0] == "nyards_road"):
                with ap.da.UpdateCursor(road, ["OBJECTID_1", "Railyards_Port_Warehouse", "Energy"]) as cur_d:
                    for row_d in cur_d:
                        if(str(row_b[1]) == str(row_d[0])):
                            row_d[1] += row_b[2]
                            row_d[2] += row_b[2]*row_b[2]
                            cur_d.updateRow(row_d)
            elif(row_b[0] == "nyards_rail"):
                with ap.da.UpdateCursor(rail, ["OBJECTID_1", "Railyards_Port_Warehouse", "Energy"]) as cur_e:
                    for row_e in cur_e:
                        if(str(row_b[1]) == str(row_e[0])):
                            row_e[1] += row_b[2]
                            row_e[2] += row_b[2]*row_b[2]
                            cur_e.updateRow(row_e)
# This part checks whether the route involved transshipment stops or not.
# Consequently it allows to identify if it was an intermodal service
# truck only trip or rail only trip. For intermodal trips, the ID of the
# transshipment locations are extracted
if (len(intermodal_data[route_name]) == 1):
    row[3] = "intermodal"
    if (ACCESS == "nyards_road"):
        row[4] = intermodal_data[route_name][0]
        row[5] = 0
    else:
        row[4] = 0
        row[5] = intermodal_data[route_name][0]
elif (len(intermodal_data[route_name]) == 0):
    if (ACCESS == "nyards_road"):
        row[3] = "truck_only"
        row[4] = 0
        row[5] = 0
    else:
        row[3] = "rail_only"
        row[4] = 0
        row[5] = 0
elif (len(intermodal_data[route_name]) == 2):
    row[3] = "intermodal"
    row[4] = intermodal_data[route_name][0]
    row[5] = intermodal_data[route_name][1]
except Exception:
    e = sys.exc_info()[1]
    print(e.args[0])
    ap.AddError(e.args[0])
cur.updateRow(row)

```